ELECTRIC
RAILWAY ENGINEERING

Purdue University Test Car.

ELECTRIC

RAILWAY ENGINEERING

BY

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PREFACE.

To students in technical universities who wish to specialize in the subject of electrical railway engineering and to those who understand the fundamental principles of electrical engineering and are interested in their application to electric railway practice it is hoped that this book may be of value.

While it is planned primarily for a senior elective course in a technical university, it does not involve higher mathematics and should therefore be easily understood by the undergraduate reader.

The volume does not purport to present any great amount of new material nor principles, but it does gather in convenient form present day theory and practice in all important branches of electric railway engineering.

No apology is deemed necessary for the frequent quotations from technical papers and publications in engineering periodicals, for it is only from the authorities and specialists in particular phases of the profession that the most valuable information can be obtained, and it is believed that a thorough and unprejudiced summary of the best that has been written upon the various aspects of the subject will be most welcome when thus combined into a single volume.

The author wishes to express his appreciation of the assistance of Mr. Emrick, instructor in electrical engineering at Purdue University, in preparing illustrations for the book and to those students who by thesis investigations have added to its value.

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PART I.

PRINCIPLES OF TRAIN OPERATION.

CHAPTER I.

HISTORY OF ELECTRIC TRACTION.

Although it is not the purpose of this treatise to relate facts, but rather to study the engineering and economic problems encountered in electric traction, yet it seems advisable to review briefly the history of the development of the electric railway by way of introduction.

Two distinct epochs were encountered in the brief period in which electric traction has come to the front. The first was that in which the experimental designs were hardly more than models operated with primary batteries. Occasionally during this period, however, enthusiasts who did not realize the insuperable financial drawbacks of primary battery operation constructed and experimented with cars of considerable size operated in that manner. Such was the car constructed by Page in 1851 for the Washington and Baltimore Railroad, which made use of a 16 h. p. motor supplied with power from two large Grove cells made up of platinum plates 11 in. square. This first epoch was soon brought to a close, however, partly by the foresight of the investigators who realized the limitations of the primary battery and partly by the failure of all attempts to commercialize the primary battery car by those who had continued to experiment therewith.

The second epoch opened, after a brief interval of inactivity, simultaneously with the development of the reversible dynamo. In the development of this machine progressive experimenters could foresee the beginnings of electric traction upon a practical basis. Bearing in mind the existence of these two periods, the history of electric traction will be considered, greatly abstracted, but as nearly as possible in chronological order.

Since electric traction has ever been dependent upon the electric motor and the latter upon the discovery by Faraday, in 1821, that electricity could be made to produce mechanical motion, the latter date rather indirectly and vaguely marks the birth of

the subject under consideration. America has the honor of first applying the electric motor to a car, model though it was, while later developments vibrated from America to Europe and back to America with a rapidity difficult to follow with accuracy. A poor blacksmith of Brandon, Vt., by the name of Thomas Davenport has the honor of first making this application of electric motor to a car in 1835, the motor having been constructed by him several years previous. During the short period of six years it is said that Davenport constructed over a hundred electric motors of various designs. That which was described as having been exhibited by him upon a car at Springfield and Boston, Mass., consisted of a revolving commutated magnet which was caused to attract stationary armatures arranged around the periphery of its path of revolution. The car thus equipped was operated upon a small circular track.

About the year 1838 Robert Davidson of Aberdeen, Scotland, built a much larger motor placed upon a battery car 16 ft. by 5 ft. in dimensions of the gauge then standard and operated same with 40 cells of battery consisting of iron and amalgamated zinc plates immersed in dilute sulphuric acid. It is of interest to note that after several successful trips over Scotland railways this car was purposely wrecked by steam railway engineers who were afraid it would supersede types in use at that time.

Two rather fundamental patents were issued in England about this time, one in 1840 to Henry Pinkus involving the use of the rails for current conductors and another in 1855 to Swear which, although applied to telegraphic communication with moving trains, comprised the basis of the present current collecting trolley. Patents were also granted in 1855 by both France and Austria to Major Alexander Bessolo which covered the same fundamental principles but which described more in detail the third rail conductor, the insulated trolley, and even suggested central station supply.

The experimental work in this country of Prof. Moses G. Farmer in 1847 and Thomas Hall in 1850 might be considered in particular because of the use for the first time of the rail as a conductor and the adoption of a geared speed reduction between motors and driving axle. The work of Page, previously men-

tioned, deserves prominent mention at this time. For many years after these experiments investigations in electric traction seemed to be dormant, largely due to the general realization of the impracticability of the battery as a source of energy.

The second era of electrical railway development opened about the year 1861 when Pacinotti invented the reversible continuous current dynamo. From this invention may be said to have arisen all modern generators and motors. While these were gradually developed by Gramme and Siemens, Wheatstone and Varley, Farmer and Rowland, Hefner-Alteneck and others, Wheatstone and Siemens having almost simultaneously developed self-exciting generators equipped with shunt and series winding, respectively, yet a considerable period of time elapsed before these developments were effectively applied to traction.

The work of George F. Green, a poor mechanic of Kalamazoo, Mich., has been quoted as the connecting link between the two eras. Although he began his experiments as late at 1875, after the development of the dynamo, his first model road reverted to the battery delivering current to the car over the operating rails. Although Green proposed the trolley for his experimental track, he did not make use of it. The following work of this man is rather pathetic, in that he constructed a car about the year 1878 large enough for two people and realized the advantages of the dynamo for supplying energy for same. He did not understand how to construct this machine himself, however, and was not financially able to procure one of the few being constructed abroad at that time. He applied, in 1879, for patents which would probably have been of considerable value at that time, but because of limited funds and the fact that he was obliged to act as his own patent attorney, his claim was rejected and only finally granted in the year 1891 after a belated appeal to the circuit court of the District of Columbia.

The first electric road operating on a practical scale was the one exhibited by Siemens and Halske at the Berlin Exposition in 1879. This consisted of an oval track about 1/3 mile in length upon which an electric locomotive was operated with three small trailers accommodating from 18 to 20 passengers. The motor was mounted with its axle lengthwise of the car and

power was transmitted to the car axle through a double bevel gear speed reduction. A speed of about 8 miles per hour was attained. The current was supplied by means of a third rail located between the running rails.

The year 1880 in Europe marked the exhibition of another model electric railway at Vienna by Egger which used the running rails for conductors. In this year also the study of a method of replacing the pneumatic dispatch system of Paris by miniature electrically propelled carriages was carried on. Siemens proposed at this time a commercial road for Berlin and endeavored to obtain a franchise for same.

The first electric road to be installed apart from an exposition was that at Lichterfelde, near Berlin, which was opened in 1881. A single motor car using cable drive between motors and axles operated upon this road which was 1 1/2 miles in length, at a speed of about 30 miles per hour. It was sufficiently large to accomodate 36 passengers. Although a third rail road when installed, it was changed over 12 years later to a double trolley system. This road has remained in continuous operation. During this year, also, the horse railroad between Charlottenburg and Spandau was changed to electric traction.

At the Paris exposition of 1881, Siemens and Halske demonstrated the use of the overhead trolley for current distribution to cars, the conductors consisting of metal tubes slotted on the underside, mounted upon wooden insulators; in which tubes, metal contactors, electrically connected with the car, were allowed to slide. In 1883, a 6-mile third rail road was opened at Portrush, Ireland, which was worthy of note because of its operation from a central station driven by water power.

Referring back to this country, Thomas Edison and Stephen D. Field began experimenting about the year 1880. Edison was principally interested in the development of the incandescent and arc lamps at this time and aside from building a short road at his laboratory at Menlo Park and taking out a few patents, he did little in this line. Field did considerable pioneer work, having made plans in 1879 for a railway to be supplied with power by means of a conductor enclosed in a conduit and using the rails as a return circuit. In 1880–81 he constructed and put into

operation an experimental electrical locomotive at Stockbridge, Mass. Patents were applied for by Field, Siemens, and Edison within 3 months of each other early in 1880. Since Field had filed a caveat, however, the year before, his papers were given priority. Field's plans, however, remained on paper until the latter part of the year 1880 which was a year later than the installation of the Berlin road.

Little more was accomplished in the United States until 1883, when the interests of Edison and Field were united and the Electric Railway Company of the United States was organized. This company exhibited an electric locomotive at the Chicago Railway Exposition in 1883, which operated on a track about 1/3 mile in length in the gallery of the exposition building. The motor operated a central driving shaft by means of bevel gears, this shaft being belted to one of the axles. The speed was varied by the use of resistances. Reverse motion was accomplished by throwing into service an extra set of brushes by means of a lever, only one set of brushes, of course, being upon the commutator at any one time.

Charles J. Van Depoele, a Belgian sculptor, who was destined to play an important part in the later development of electric traction, entered the field in 1882–83 when he operated a line in connection with the industrial Exposition at Chicago. After installing equipments at the New Orleans Exhibition and at Montgomery, Ala., and putting roads in operation at Windsor, Ont., Detroit, Mich., Appleton, Wis., and South Bend, Ind., the company which Van Depoele had formed was absorbed in 1888 by the Thompson Houston Co., which had recently been organized. The name of Leo Daft was one that cannot be neglected in the development of this period, for after considerable work with stationary motors in 1883 he constructed a locomotive capable of hauling a full sized car. The control in this car was brought about by varying the resistance of the motor field for which purpose some of the coils were wound with iron wire in place of copper. The company organized by Daft at Greenville, N. J., installed roads at Coney Island, N. Y., and the Mechanic's Fair in Boston, and in 1885 equipped the Baltimore Union Passenger Ry. Co. with electric locomotives. During

this year electric traction was applied by this company to the Ninth Avenue lines in New York, but after a few experimental runs of the locomotive termed the "Benjamin Franklin" the experiment was abandoned.

In 1884 Bentley and Knight installed a system in Cleveland, Ohio, which was probably the first to come into active competition with a horse car line. Two miles of track were operated with under ground conductor in wooden slotted conduit. Motors were connected with car axles through the agency of wire cables.

The railroad installed in Kansas City, Mo., in 1884, by J. C. Henry was noteworthy for its departure from other designs and its adoption of features which have since become standard practice in electric railroading. Henry claims to have introduced the use of the overhead trolley. Whether this be true or not, the word "trolley" was first coined by the employees upon this road as a contraction for "troller" the word first applied to the four wheeled carriage which was used on the overhead wire as a current collector and connected with the car by means of a flexible cable. The use of the trolley rope for replacing the trolley was of much more significance than it would at first appear because of the fact that it was formerly customary to hire a boy to ride on top of the car to keep the trolley on the wire. The present system of span construction and feeder installation was first developed by Henry on this road. His overhead conductors consisted of two No. 1 B. & S. bare copper wires spliced every 60 ft., for this was the greatest single length procurable at this time. The rails used were those which had been installed 12 years before for horse car service and weighed but 12 lb. per yard. They were at first bonded by driving horse-shoe nails between the fish plates and the rails. The motor was a 5 h. p. Van Depoe e type connected with the axles by means of a clutch and a five speed differential gearing. The generator was a series arc machine of 10 h. p. developing a voltage up to 1000 volts. Although Henry was able to mount 7 per cent. grades without difficulty, the Cleveland road was the only other practical road operating in America at that time and it was extremely difficult to gain the confidence of the public.

Of the roads that were installed during the next few years,

the one which gave the greatest impetus to electric traction and the one often quoted as the first electric road in the United States was that in Richmond, Va., equipped in the year 1888 by Frank J. Sprague. At this time Mr. Sprague was already prominent in the railway field, although much of his time had been given to the development of the stationary motor. In a paper befoie the Society of Arts of Boston in 1885 he had advocated the equipment of the New York Elevated Railway with motors carried upon the trucks of the regular cars. In 1886 a series of tests were carried on upon the tracks of the 34th street branch of this road. These experiments, like many previous ones, however, were finally suspended because of the impossibility of interesting the railway management sufficiently to launch out upon a commercial installation.

The motor design and suspension used by Sprague in these tests were the forerunners of present construction and therefore worthy of a brief description. The motor frame contained bearings mounted upon the car axle, thus permitting the former to swing slightly about the axle as a center keeping the gear and pinion always in mesh on rough track. The other side of the motor frame was hung from the truck frame by means of springs. Single reduction gearing was used. Two motors were used on each truck but they were open to the weather. The first designs were shunt wound but later types made use of a series compensating winding. Control was obtained by resistance in both armature and field circuits. The motors were used for returning energy to the line as well as for braking.

Before considering further the rather important installation at Richmond, it is well to consider a census of electric traction development early in 1887. In Europe at this time there were but nine installations including but 20 miles of track taking into consideration every type of electric traction including that in mines. In the United States there were 10 such installations involving 40 miles of track and 50 motor cars. Public prejudice had not been overcome and no system of any size had been operated commercially.

The Sprague Electric Railway and Motor Company, contracted for installations at St. Joseph, Mo., and Richmond, Va., during

the year 1887, the latter contract covering a complete new road including generating station, overhead lines, and the equipment of 40 motor cars with two 7 1/2 h. p. motors each. It was placed in operation in February, 1888, and many were the new experiences and amusing anecdotes connected with this installation. The distribution system consisted of an overhead conductor mounted over the center of the track with a second parallel conductor on the pole line supplied with feeders from the power station and extending to various distributing points. The power station was equipped with six 40 k. w. 500 volt Edison generators driven by three 125 h. p. engines. Upon each axle of the car was mounted an exposed motor in the manner previously described. The single reduction gearing employed at first was later replaced by the double reduction type. The speed control was effected by two separate switches, one changing the field connections from series to parallel and the other making similar changes in the armature circuit. The cars could be operated in either direction from either end and the entire weight of the car was available for traction. Motors were operated in both directions, at first with laminated brushes fixed at an angle and later with radial solid metallic brushes. The success of this road at Richmond, in the face of many reverses and new engineering problems which had to be overcome, was probably largely due to the fact that Mr. Sprague was the first man with a competent education to enter the field. With this technical training together with his familiarity with the failures of other experiments and the development of the stationary motor with which he was closely allied, he was able to solve the many difficult problems which arose and place this road on a practical operating basis.

From this date electric traction became firmly seated and its future development was rapid, the natural tendency being toward heavier equipment. After investigation of the Richmond system the West End Railway of Boston soon adopted electric traction. In 1890 the South London road was equipped with electric locomotives and three years later the Liverpool overhead electric railway was put in operation. Third rail trains of four motor cars, equipped with hand control, hauling three trail care were used at the Chicago World's Fair in 1893 and in 1896 the

Nantasket branch of the New York and New Haven Railway was electrified. September of the same year saw the Lake Street Elevated of Chicago begin electrical operations and two months later electric service was begun on the Brooklyn Bridge.

Since it is impossible to further list the new electric roads coming into existence the following table will be of value in pointing out the remarkable growth of the electric railway in the United States.

TABLE I.

GROWTH OF ELECTRIC TRACTION IN UNITED STATES.

Year.	No. electric roads.	Miles track.
1889	50	100
1890	200	1200
1891	275	2250
1894	606	7470
1895 (July)	880	10863
1902	739	22000

Note.—The decrease in the number of companies from 1895 to 1902 is probably due to the large amount of consolidation going on during this period.

The most important changes in motor design that came with this progressive movement of the electric railway were the enclosing of the frame to protect the motor from the weather, the replacing of cast iron by steel, the change from two to four poles, the use of form wound coils and carbon brushes and the return to the old single gear reduction between motor and axle. The control system of 1892 made use of the combined resistance and series parallel connection, which is recognized as good practice to-day while the introduction of the blow out magnet was a long step forward in controller design.

The more recent developments in electric traction comprise the use of alternating current for transmission to substations, the multiple unit control of the various cars of a train from a single master controller, the use of alternating current motors on the car, the electrification of steam roads with the more powerful electric locomotives, and the use of high voltage direct current system. These problems are of such a broad nature and so im-

portant in the study of modern practice that they will be taken up more in detail elsewhere. Suffice it to say, by way of historical comment, that the rapid introduction of interurban railways beginning about the year 1894, together with the advances made in transformer design by Stanley, in polyphase transmission by Ferraris and Tesla and in the synchronous converter by Bradley and others brought about the first of the above mentioned changes, *i.e.*, the use of alternating current for transmission purposes. Probably the first proposal to use such a system with substations was the one made by B. J. Arnold in 1896 for an interurban road to run out of Chicago. Although this particular line was not built, a similar system was installed about two years later. The multiple unit system was developed by F. J. Sprague who proposed its application to the New York Elevated Railway in 1896. After several vain endeavors to secure its adoption it was finally installed the following year by the South Side Elevated Railroad of Chicago and is now in common use on elevated systems and is used to some extent in interurban traction.

Summarizing briefly, the most prominent names in the development of the electric railway are found to be those of Faraday, Davenport, Farmer, Hall, Pacinotti, Siemens, Green, Field, Van Depoele, Daft, Bentley, Knight, Henry, and Sprague. While gradual developments have been going on more or less irregularly since 1835, the practical electric railroad, operating upon a commercial scale, dates back to about the year 1888. Vast strides have taken place since that date, however, until at the present time electric traction is the recognized transportation system in practically all cities and towns. It has tied together the larger cities with facilities for rapid passenger transit and for the transportation of both express and freight. It has opened up the city markets for the farmer of the small town, and the country suburbs for the residences of the city business man. It has competed successfully with the steam roads on interurban lines; it has found a foot-hold in the city terminals of the former, and is at present being seriously considered and in some particular cases has been adopted and successfully tried out for trunk line service. Rightly has it been said that its growth is without a parallel in the history of American invention and industrial progress.

CHAPTER II.

Traffic Studies (Predetermined).

One of the first considerations in connection with the planning of a new railroad or of an extension to an old system, whether it be within the limits of a city or an interurban line, is the study of probable traffic. Upon such a study is based the predetermination of gross income, train schedules, and power station demand. The importance, therefore, of an accurate and detailed study of all the factors which may affect the traffic upon a given road need not be emphasized further.

Population.—A study of the railway census will disclose the fact that there is a fairly dependable relation between passenger traffic and population for both urban and interurban railroads. In the latter case, of course, the population under consideration must be that of the two terminal cities and, in most cases, a portion of the intermediate population which may be considered as tributary to the line. The determination of this tributary population is rather difficult, being largely dependent for its accuracy upon the experience and judgment of the engineer. In general, however, it is usually taken as the population of a strip of territory from 1 1/2 to 2 miles in width on either side of the proposed railroad and parallel thereto. The population of such a strip may be determined by actual canvass or it may be assumed that the township or county through which the road extends is evenly populated throughout the rural districts. If this be true, the tributary population may be found from the following proportion.

$$\frac{\text{Tributary population}}{\text{Township population}} = \frac{\text{Area strip.}}{\text{Area township}}$$

The township population may be obtained from the census reports and the required areas scaled from a map of the territory in question.

While it will be found advisable to make an analysis of the

relation between population and passenger traffic per year, mileage of track economically operated, gross income, etc., for the entire country, a table or series of curves covering such data obtained from the particular locality in which the proposed road is to be operated will be found of more value. The nearer the conditions of installation and operation of these roads approach those of the proposed road, the more dependable will be the results based thereon.

A table giving data of value in predetermining the traffic and gross income for a proposed road is given herewith for cities of the middle west under 25,000 population.

TABLE II.

ELECTRIC RAILWAY STATISTICS.[1]

City.	Population.	Total.	No. passengers per unit population.	Total.	Miles track per 1000 population.
Alton, North Alton, Upper Alton, Ill.	17,487	1,497,130	85.6	12.25	0.70
Cairo, Ill.	12,566	870,838	69.3	9.67	0.77
Kankakee, Bradley, Bourbonnais, Ill.	15,708	714,769	45.5	12.78	0.81
Vincennes, Ind.	10,249	450,000	43.9	8.00	0.78
Burlington, Ia.	23,201	1,600,000	69.0	14.50	0.62
Ashtabula, O.	12,949	999,857	77.2	5.75	0.44
Lima, O.	21,723	1,375,979	63.3	18.55	0.85
Tiffin, O.	10,989	482,000	43.9	7.33	0.67
Zanesville, O.	23,538	1,800,000	76.5	10.00	0.42

Whereas such a table offers more opportunity for the correct comparison of traffic, etc., for an urban road or for extensions to such a system than for the predetermination of interurban traffic, yet the methods outlined may be used to advantage in interurban developments providing they are applied with conservative judgment based upon successful interurban experience. As an example of such adaptation of data to interurban practice it should be noted that a different proportion of terminal population will be tributary to the traffic of the proposed road in each

[1] Taken from Railway Census, 1902.

case under consideration. In the case of the road being the first to enter a relatively small terminal city, a large portion of the population of the city will avail itself of the road, but if the road is the fifth or sixth to enter such a city, as Indianapolis or Chicago, a relatively small portion of the population of the terminal city can be counted upon for passenger traffic. It follows directly from this, therefore, that with a large terminal city, the earnings of the road per capita of terminal population will be small and the earnings of a successful road per mile of track will be relatively large and *vice versa.*

Growth in Population.—It is necessary, however, to know more than the present terminal and tributary population. The growth of both for several years to come must be predicted. In order to do this intelligently it is necessary to know the growth in the past not only, but to study the causes of any eccentricities in the growth curve. It is only after such a detailed study that the population curve may be accurately extended to determine the population to be expected forty or fifty years hence.

Bion J. Arnold, consulting engineer of Chicago, in his "Report on the Chicago Transportation Problem," points out very clearly the fallacy of predicting the population for any considerable term of years by any rate of growth which has existed in the past, if the law of "Yearly decrease in the rate of increase" be neglected. If, by way of illustration, we refer to the curve of Fig. 1 which represents the population of the city of Philadelphia during a long term of years, we shall see at once that had the future population of that city been predicted in 1860 from the rate of increase during the previous decade, the result would have been far from the fact. As a matter of fact, the rate of increase in population of Philadelphia dropped in five years from 33 per cent. per annum to 9.7 per cent. and, in another five years, to 2.9 per cent. Although this marked change in the rate of increase of population is exceptional in the case of Philadelphia, Arnold found that in the cases of the eight largest cites of the world which he studied the average rate of increase in population is gradually decreasing. It is obvious, therefore, that even if the average rate of increase in population over a long term of years were applied to the future growth of a city,

the results would still be too high. As an illustration, the average rate of increase in Chicago from 1837 to 1902 was 8.6 per cent. per annum, from 1892 to 1902 it was 4.9 per cent., and during the year 1902 it was 7.7 per cent. Beginning with the year 1900 and compounding the population at 5 per cent., the resulting value for the year 1952 would be 18,500,000, while an 8

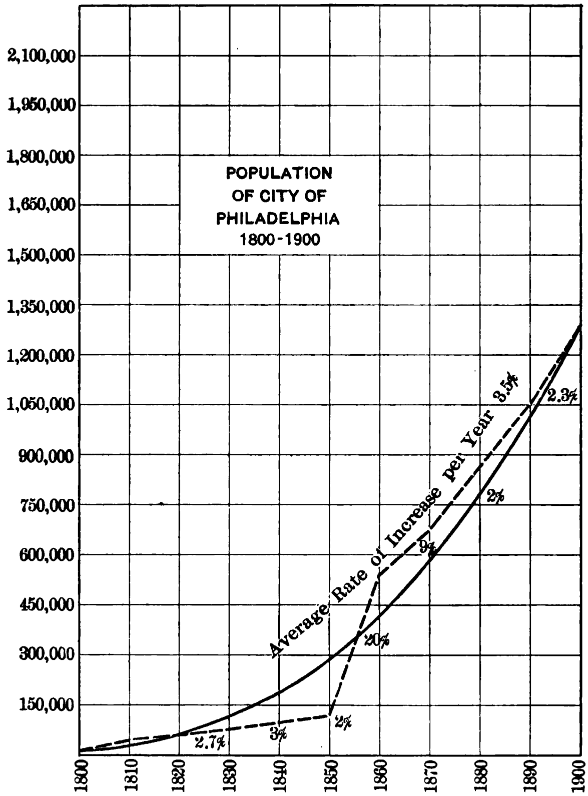

FIG. 1.

per cent. increase, compounded, would give this city a population of 26,500,000 in only 35 years. With the use of the more correct method, however, which takes into consideration the fact that the rate of increase is continually on the decline, the population is compounded with a constantly decreasing percentage. Such a method applied to the city of Chicago and beginning with the 1902

rate of 7 per cent. results in a predicted population of 13,250,000 for the year 1952. It is probable that this will mark the upper limit of the actual population curve, while the minimum limit of the area within which the population will fall in the next fifty years will be determined by a similar method of reasoning beginning with an increase rate of 3 per cent. which represents the

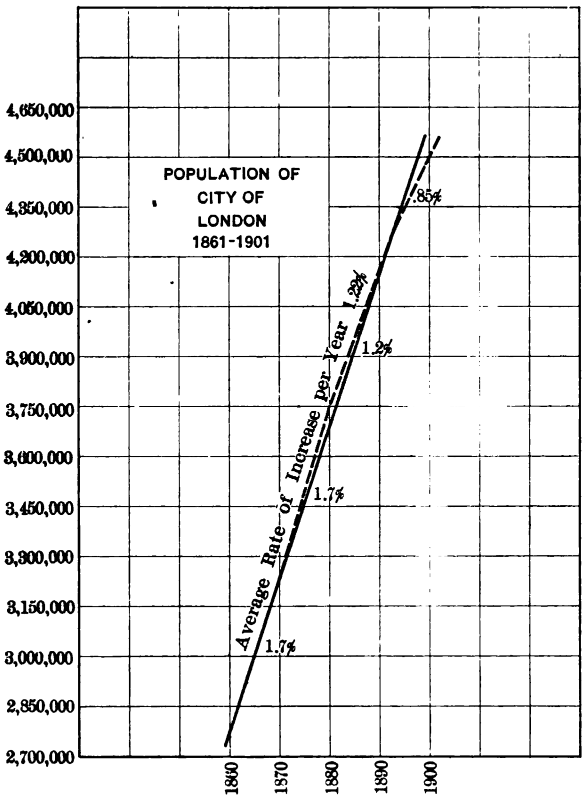

FIG. 2.

average growth of the large European cities. The result of the latter calculation gives Chicago a population of 5,250,000 in 1952.

Reference to Figs. 2, 3, and 4 will give an idea of the changing rates of increase in population of the cities of London, Paris, and New York respectively. Several decades will be noted in these curves during which these rates have been abnormal; which rates,

if used as a basis for the predetermination of future population, would lead to very erroneous results.

Riding Habit.—The proper determination of the "riding habit" for a given community or the number of passengers per capita of population per annum is important if the traffic of a proposed road is to be correctly predicted. This is always a

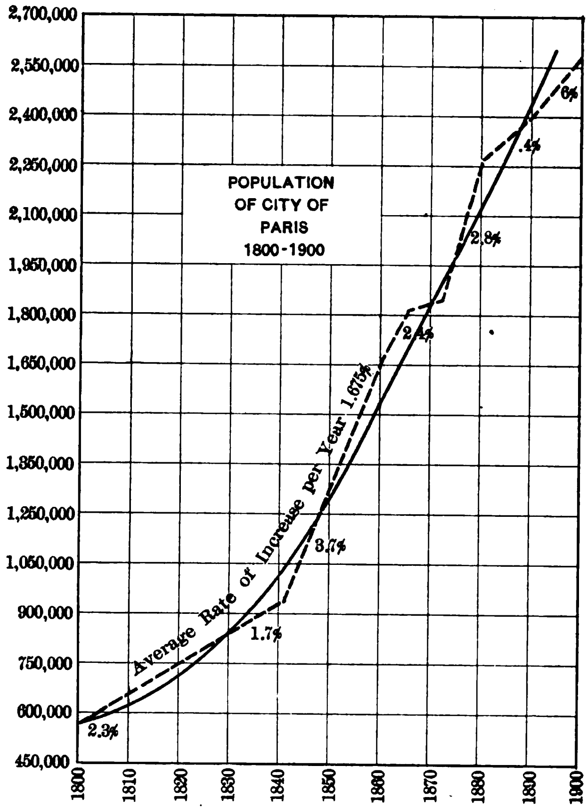

FIG. 3.

local problem, dependent upon the geographical and industrial features of the country or city under consideration, as well as upon the customs of the people, the existing or possible forms of recreation, etc. In the case of the interurban road little aid can be obtained from tabulated results upon other roads for the possibility of comparison with a road where the conditions

outlined above are the same is very small. For urban roads, however, reference may well be made to a curve (Fig. 5), plotted between "passengers per capita per annum" and population throughout the country. This curve has been shown by one author[1] to rise from approximately seventy passengers per capita

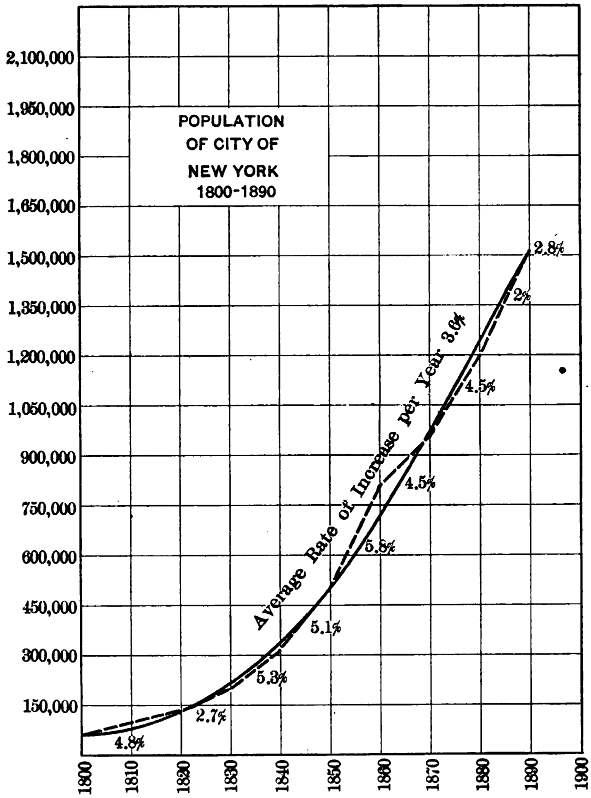

FIG. 4.

per annum in cities of 15,000 population to a constant value of 240 in cities of 1,000,000 inhabitants and over, although Arnold's results in Chicago show an increase from 150 to 182 passengers per capita per annum from 1891 to 1901.

Competition.—The question of competition with steam roads

[1] See "Electric Railways," Vol. II, by S. W. Ashe.

is a vital one with most interurban and suburban railroads, whereas most urban systems are practically monopolies.

If the proposed road is to parallel a steam line, it is usually advisable to make a study of the traffic conditions on such an existing line, either from authentic records or by actual counting of passengers on all trains in the various seasons of the year. Such records must be applied with great caution, however, for it has been found that a well equipped interurban line with frequent and high speed service often takes away much local traffic

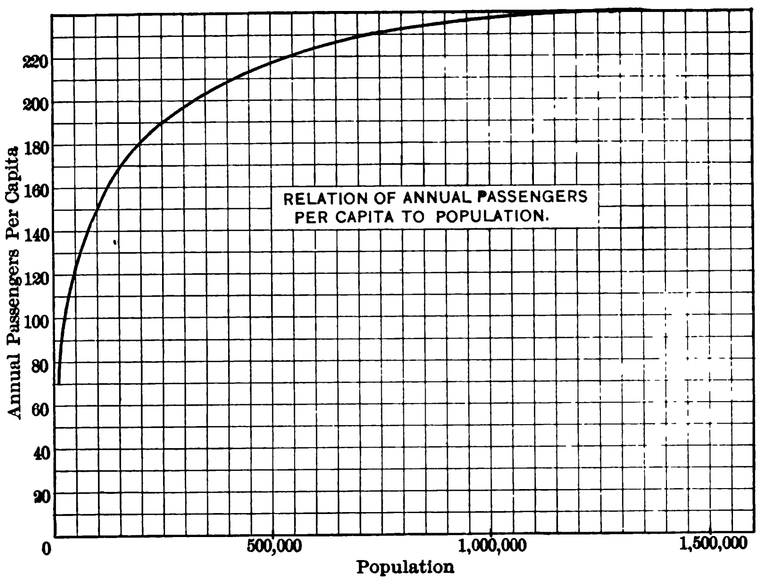

FIG. 5.

from the parallel steam lines not only, but, in addition, creates a traffic of its own. In other words, if the public can make a trip at any time of the day desired; if the cars are clean, free from smoke and cinders, and comfortable, and if the time lost en route is a minimum, it has been found that many ride who would otherwise remain at home. It is difficult to obtain more than a very rough approximation, therefore, of future traffic from steam railroad statistics. That preference is given to the electric road and that traffic is often greatly reduced on existing steam lines with

the advent of the electric interurban line is clearly shown by the figures on the following table.

TABLE III.

TRAFFIC ON LAKE SHORE AND MICHIGAN SOUTHERN BETWEEN CLEVELAND AND OBERLIN [1]

	Westbound.	Eastbound.	Total.	Average per month.
1895..........	104,426	98,588	203,014	16,918
1902..........	46,328	45,433	91,761	7,647

Gross Income.—After having studied all statistics and local conditions which may possibly have a bearing upon the future traffic of a proposed road and having approximated from such study, combined with the riding habit of the people, the total traffic that may be expected with its hourly, daily, and season wide fluctuations, it will be necessary to determine the gross income possible from such a road. This may be done either by applying the average fare paid per passenger to the above traffic figures, which total may be augmented in some cases by express, freight, and mail receipts; or a comparison may be made with other similar roads operating successfully in the same locality and under similar conditions. Such a comparison based upon units of gross income per capita of terminal or tributary population or per mile of track gives very satisfactory results, as will be seen from the following example.

In determining the gross income for a proposed fifty mile electric interurban line in Texas, connecting cities of 34,000 and 58,000 inhabitants, comparison was made with two other roads operating under similar conditions with the following results.

One of these roads, in the same state, connected cities of 15,000 population each with 16 miles of track, returning a gross income in 1905 of $3.48 per capita of terminal population, while the second road, 81 miles in length, connecting cities of 26,000 and 52,000 population, earned a gross income of $8.45 per capita. Taking the more conservative value of $3.48 from the former

[1] See "American Electric Railway Practice," by Herrick and Boynton, p. 4.

road as a basis, the minimum return from the new road should be approximately $92000 \times \$3.48$ or $321,000, representing an earning of $6,420 per mile. This figure compares very favorably with the corresponding values of $8,160 and $6,540 per mile for the two roads previously referred to.

In order to determine the net income it would be possible, of course, to approximate the operating expenses, fixed charges, etc., in detail, and subtract them from the gross income. A fair average ratio of net to gross income is often taken, however, as 45 per cent. This figure applied to this particular road shows a net income of $144,500 annually and therefore a possible operating expense of $176,500.

Number and Capacity of Cars.—The determination of the number and therefore the necessary carrying capacity of cars is sometimes arrived at as follows:[1]

A well conducted road may safely be assumed to earn twenty cents per car mile. The car mileage per year may therefore be roughly obtained by dividing the gross income by the factor (0.2). The number of car miles per hour are, of course, readily deduced from the above quotient by dividing by the hours of actual car operation per year. If, then, the average schedule speed is specified by city ordinance or is decided upon by the railway officials, the number of cars may readily be determined from the equation

$$\text{Number of cars} = \frac{\text{Car miles per hour.}}{\text{Schedule speed in miles per hour.}}$$

However, the above result can be more satisfactorily and correctly obtained in most cases from train schedules. The total traffic to be expected having been calculated as explained above, the headway or schedule speed of cars is usually readily decided upon with a view toward carrying this amount of traffic or in order to successfully meet the competition of parallel steam roads. The graphical train schedule sheet explained in detail in Chapter IV may then be plotted, whereupon the number of cars necessary to maintain the proposed schedule immediately becomes apparent.

It would be possible, of course, to determine the seating capacity and size of cars to be purchased for a given road from the theo-

[1] See "Electric Railways" by S. W. Ashe, p. 16, Vol. II.

retical calculation of the probable number of passengers per trip at various times of day and at various seasons of year but such calculations seldom, if ever, become controlling features in the purchase of cars for a given road. For interurban roads the size and capacity of cars have been very well standardized by custom, the increased traffic at times being handled by changes in schedule or by the operation of two or more cars together in a train on the same schedule. As will be seen in the following chapter, however, cars are seldom operated at their exact seating capacity and in spite of the fact that standing in cars on interurban trips becomes most tedious and oppressive and, granting the conclusions discussed more at length in the following pages that a considerable percentage of passengers stand in cars by preference, yet it is a regrettable fact that the size and headway of cars on many roads, especially in cases of urban traffic, are determined with but little consideration of the ratio of seating capacity to passenger traffic.

CHAPTER III.

TRAFFIC STUDIES (EXISTING).

The necessity of making a careful study of existing traffic upon urban, interurban, and even steam railroads for the purpose of comparison with the conditions of a proposed line and in order to intelligently predetermine the probable income from, and therefore the advisability of financing and building a new line, has already been set forth. Further than this, those responsible for the successful operation of present and future lines must continually study the condition and tendencies of traffic. Quoting from a recent editorial in the Street Railway Journal upon this point, "The managers of city railway systems which do not embrace more than a half-dozen routes usually feel that they know every detail of the traffic distribution so well that it is unnecessary to go to the trouble of preparing graphic records. The correctness of this point of view, however, is not proved by the experience of those who have had occasion to prepare traffic curves, even for cities of less than 40,000 population, as they have found that such curves will betray the riding peculiarities of the public much more clearly than a mere tabulation. From such a record, for example, it is easy to observe whether the passengers take kindly to short trip cars or neglect them in favor of through cars even when they do not ride to the end of the line.

"Traffic curves, furthermore, are not only of value to the company in making up its schedule, but are also an aid in its relations to the public. When a complaint is made about the service on a certain line, it is surely convenient to be able to prove graphically that in the course of the day's operation the number of seats furnished far exceed the passengers and that the schedules adopted are based strictly upon the amount of traffic which the line brings."

While reports of traffic investigations have been made public from time to time, especially as the results of studies by consulting

engineers in connection with proposed improvements to the railway system for the purpose of reducing congestion of traffic by means of subways, elevated lines, rerouting of cars, introduction of prepayment cars, etc., yet little has been said regarding the best methods of making such detailed studies with any degree of accuracy. In fact the difficulty in obtaining accurate and dependable results has often been given as an excuse for not undertaking such a study. It is also true that where conditions of traffic are most variable, and these difficulties, therefore, most pronounced, the need of such an investigation is usually greatest and, when undertaken, results in the greatest possible improvement in service.

It has been found where these traffic studies have been successfully made that it is necessary to obtain data entirely independent of the daily returns of employees and that these data should be obtained by a crew of technically trained observers who understand the significance of every reading taken. The average car employee, no matter how loyal and conscientious, usually not understanding the use to be made of the data collected and the relative accuracy with which the various readings should be taken, has been found unsatisfactory for this work.

It is usually advisable to subdivide the city roughly into districts such as business, manufacturing, residence, etc., and then to make a detailed study of the riding habits of the people and the loading of the cars on a single route or division at a time. It will at once be observed that the day may readily be divided into several periods of peak load, usually four in number. One city whose traffic conditions were investigated recently by the Wisconsin State Commission was found to have its four periods of peak load extending from 6.00 to 9.00 A. M., 11.00 A. M. to 2.00 P. M., 5.00 to 8.00 P. M., and from 10.00 to 11.00 P. M., respectively.[1] The last was, of course, the theatre period and was therefore limited to a small district of the city.

In studying the problem further, it is usually found that the public at large has a very well defined habit of travel which does not vary greatly from one end of the year to another. Pleasure seekers and shoppers, of course, are irregular in their move-

[1] Graduate Thesis, Purdue University, 1910, by R. W. Harris.

ments, but the majority of passengers will soon be found to follow a definite route in their traveling, not only, but certain classes may be depended upon to ride during certain periods of the day. The above mentioned residence districts of the city and the passengers as well may, therefore, be still further subdivided as follows:

1. Business or professional.
2. Clerk and shoppers.
3. Laborers.

With such classifications in mind, it is necessary that the inspectors ride over the route or division under investigation a number of times during all periods of the day and in all kinds of weather to note roughly the effects of time of day, weather, and all local conditions upon maximum traffic. Especial notice should be taken of the stops which are of most importance, *i.e.*, those at which most passengers leave and board cars.

After such preliminary study the number of inspectors necessary, the particular stops to be studied, data to be recorded, and the number of readings to be taken in the detailed investigation may be decided upon. These readings may be taken by inspectors, provided with stop watches located at the principal stopping points; or, if the number of cars is not too great, an inspector may be assigned to each car on the route. In general the observations to be made at the most important stops are as follows:

1. Line (route).
2. Period of day.
3. Exact time.
4. Direction of car.
5. Number of car.
6. Total number of people on car.
7. Number of people standing in front vestibule.
8. Number of people standing in rear vestibule.
9. Number of people getting off car.
10. Number of people getting on car.
11. Class of passengers.
12. Conditions of vehicular traffic.
13. Conditions of pedestrian traffic.

With symbols to represent many of the above conditions upon data sheets carefully prepared in advance and with a little experience on the part of the inspector, the above data have been found to be readily and accurately taken. In fact in the investigations above alluded to check observations, taken independently but at the same time and place, varied less than 5 per cent. This is sufficiently accurate for the determinations desired.

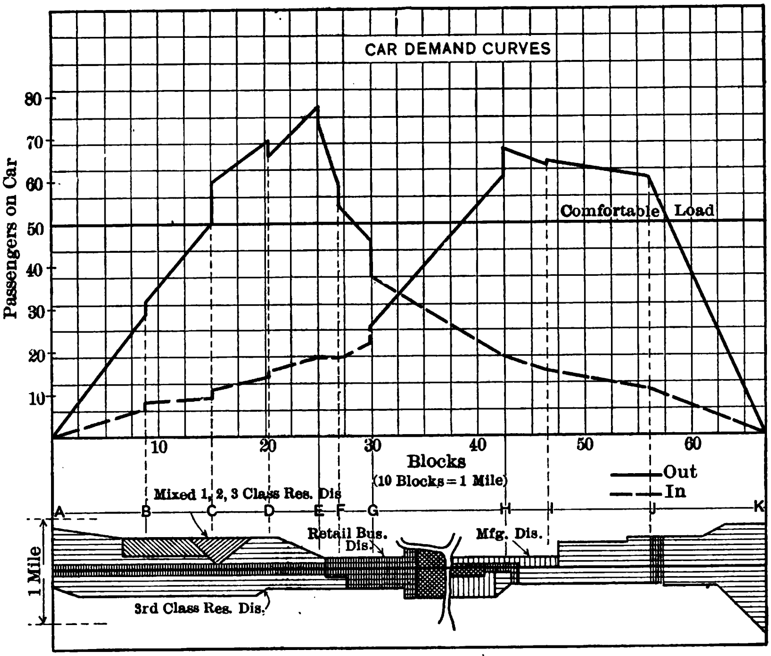

FIG. 6.

The results of an extensive investigation carried on in this way in one of the large cities of the west are typified by the single example represented by Fig. 6, in which the shaded areas represent the various districts served by the particular car line under consideration, while the ordinates of the upper curve represent the passengers on the car during the period of maximum traffic extending from 5.00 to 8.00 P. M. The abscissæ of both curves represent the distance in miles on either side of the center of the city, while the full lines and dotted lines of the upper curve

represent out-going and in-coming cars, respectively. It will be readily seen that the traffic at this time of day is largely from the city outward, as would be expected. Another point of significance is the fact that out-going cars from G to A take on the greater portion of their passengers between G and E which is the retail business district of the division, and deposit them principally between C and A which is in the mixed residence district. These passengers may properly be classed therefore as "clerks and shoppers." On the other hand the cars running from G to K

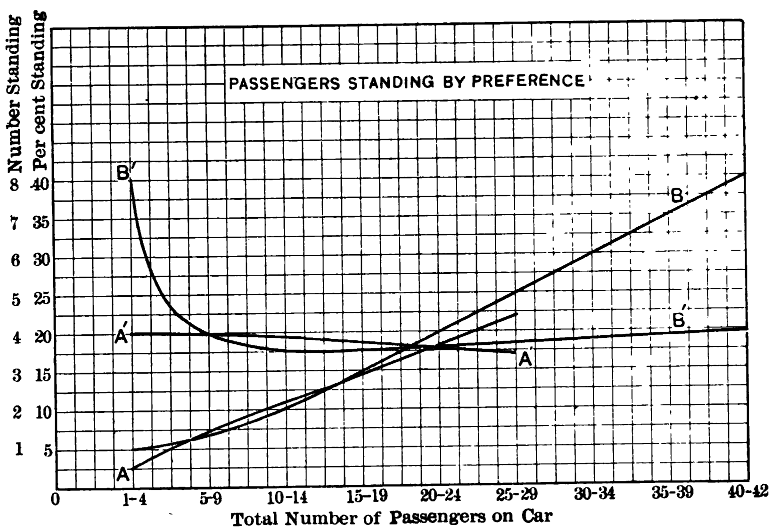

FIG. 7.

take on their passengers between G and H within the wholesale business and manufacturing districts and deposit them between I and K in the third class residence district. This leads us to classify this traffic as "laborers." In a similar manner it is possible to determine from curves resulting from careful investigation the tendency and amount of traffic on each division at all times of day.

In order to determine, however, whether or not sufficient cars of ample capacity are being supplied, the "comfortable load" per car must be decided upon. During such investigations in several of the larger cities it has been found that a considerable

number of the passengers on a car stand by preference. In Fig. 7, curves A and A′ show the total and percentage increase respectively of passengers standing by preference as the number of passengers on the car increases in a city of 25,000 population, while curves B and B′ show curves of similar tendency for a city of 330,000 in the Middle West. Referring to curve B and with the knowledge that the cars operated in this city will seat 42 passengers, it will be noted that when the car is fully loaded, eight will, on the average, stand by preference. The comfortable load has therefore been taken as 50 passengers and the variation of the "car demand" curves of Fig. 6 above and below the "comfortable load" line indicates at once the quality of service being rendered.

It cannot be reasonably expected by the public that sufficient cars shall be furnished to enable every one to have a seat at all times of day, for many of the peak loads come on so suddenly and often so unexpectedly that it would be impossible to have the necessary cars at the proper time and place if it were the policy of the company to accomodate the peak traffic with seats. Most progressive companies, however, endeavor to meet the just demands of the riding public and therefore should determine those demands from time to time by methods similar to those outlined above.

CHAPTER IV.

TRAIN SCHEDULES.

Having studied in the two previous chapters the important elements underlying the determination of probable traffic on a new railway line or upon the extension to an old system, it becomes necessary to establish the train schedule. As has been previously inferred, this is often a question of judgment to be exercised by the executive head of the road in view of the necessity of meeting competition. That is to say, the engineer who plans the details of the train schedule is instructed to arrange for hourly or half hourly interurban service, as the case may be, or the headway expressed in minutes or distance between cars in feet may be specified in the urban system. In both types of system the limiting schedule speed is usually stipulated, often by the municipalities involved. The interurban system is usually limited to two or more different schedule speeds, the higher velocities being confined to operation over private right of way and the lower within city limits or upon particularly dangerous sections of track such as trestles, draw-bridges, and temporary construction.

Whereas the hours of train arrival and departure are usually placed in the hands of the public in the form of time tables, the most convenient and common form for the study of these data by railway engineers is the graphical chart. Many factors entering into the proper construction and successful operation of a road are at once apparent from such a chart or graphical train schedule. This train schedule is often plotted with time of day in hours and minutes as ordinates and distances expressed in miles as abscissæ. It is convenient if the ordinates representing the hours be designated by heavy lines on the coordinate paper and if the hourly sections be subdivided into sixths or twelfths, representing ten and five minute intervals respectively. Upon the

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distance scale it is customary to designate the distance between stations and the location of any points of especial engineering interest along the line such as branch lines, railway crossings, city and township limits, etc. With the scales of coordinates thus determined, a series of slanting lines, Fig. 8, may be drawn to represent the progress of the train from station to station. The slope of these lines is, of course, dependent upon speed, the co-tangent of the angle which they make with the horizontal representing the schedule speed of the train. A chart made up of such straight lines representing each train leaving the terminals of the line in either direction is sufficiently accurate for a rough preliminary study of traffic possibilities, power requirements, and substation locations, but before exact time tables can be adjusted and meeting points determined, a very much more accurate and detailed graphical train schedule must be drawn. Such a schedule involving three different schedule speeds over the various sections of road as well at the representation of the time elapsed in making station stops, is shown in Fig. 9, which is the proposed train schedule for a 50.6 mile interurban line, planned to connect the cities of Galveston and Houston, Texas, within whose limits the schedule speed was confined to 10 m. p. h. It should be noted that speeds of 30 m. p. h. and 55 m. p. h. are adopted for portions of the private right of way, while one minute has been allowed for the average station stop. Such a graphical schedule enables one to predetermine not only the number of cars necessary to maintain a given schedule and the position of those cars at any moment, but it locates the meeting points, which are designated by the crossing of the schedule lines, and, when used in conjunction with the power curves of the various cars, it aids in locating substations and in determining the average and maximum loads on substations and power station. Comparing Figs. 8 and 9 it will be noticed that while the former has the same through schedule speed as the latter and while all considerations based upon the headway and the time of leaving and arrival at terminal cities taken from Fig. 8 are quite as accurate as those taken from the more detailed chart, Fig. 9, yet it is clear that nothing of value can be learned from the former regarding the meeting points nor the positions of trains at any moment.

Although local conditions will prevent any extensive comparison of train schedules of different roads or even the schedules of the same road at different seasons of year, yet it is believed that the principal factors to be borne in mind in plotting schedules can best be outlined by a more detailed study of the particular schedule of Fig. 9.

This schedule is one proposed for maximum summer traffic. It has not been tried out in actual operation, and it is quite probable that hourly headway in place of the half hourly train spacing will best meet the demand. It will be noted that the first trains in the morning leave both terminals simultaneously at 6.00 A. M., and make the run in one hour and forty-five minutes requiring a through schedule speed of $\frac{50.6 \times 60}{105} = 29$ m. p. h. Further reference to the schedule will show that of this total time only 43 minutes is spent on the private right of way where the maximum speed of 55 m. p. h. is possible. While all trains stop at all stations within the city limits, there are a number of flag stops between these limits which tend to make the operating schedule irregular but which for convenience in plotting can be represented fairly accurately by allowing three flag stops for each train between the Southern Pacific Railway crossing and that of the T. C. T. Co., at which crossings all trains are required to stop.

The corresponding points of meeting as graphically determined fall sufficiently close together to be provided for by the six sidings shown at B, C, D, E, F, G, which are approximately 1 mile in length. These could be materially shortened by varying the running time slightly. The meeting places within the city limits are so numerous that a double track extending from 6 to 7 miles out of the city terminals would seem advisable from this preliminary study.

The time table below, which was taken from the graphical schedule represented by Fig. 9, will be self explanatory and a comparison of the table and chart will illustrate the advantages of the graphical method even if the time table were to be the only result obtained therefrom.

9:30

9:00

8:30

8:0

7:3

7:0

6:3

6:0

G

TABLE IV.

TIME TABLE.

Stations.	North.					South.				
Galveston	6.00	6.30	7.00	7.30	8.00	7.45	8.15	8.45	9.15	9.45
Genoa	6.39	7.08	7.39	8.09	8.38	7.04	7.35	8.05	8.34	9.05
Webster	6.48	7.18	7.48	8.18	8.49	6.55	7.27	7.56	8.26	8.56
League City	6.52	7.21	7.52	8.22	8.52	6.52	7.23	7.52	8.23	8.52
Dickinson	6.56	7.25	7.57	8.26	8.56	6.47	7.19	7.48	8.18	8.48
LaMarque	7.05	7.36	8.06	8.35	9.06	6.38	7.09	7.38	8.09	8.39
Houston	7.45	8.15	8.45	9.15	9.45	6.00	6.30	7.00	7.30	8.00

It has been previously stated that one of the advantages of the modern interurban system in competition with steam roads is its ability to transport the passenger to more nearly the exact point in a terminal city to which he wishes to go and often gives him transfer privileges upon the local railway system if necessary. When comparing, therefore, the graphical train schedule of the interurban line with that of the competing steam road, especially with regard to the relatively long time required by the former within the city limits, it is often advisable to add to the steam schedule the walking time from terminal station to a point representing the average destination of the travelling public if such can be found. Such "walking schedule" lines added to the train schedule often bring out very striking facts in favor of the electric railway as a popular choice of means of transportation.

The particular schedule taken for illustration is a relatively simple one. With the addition of limited and local service and possibly freight and mail trains, and, in some cases, the necessity of meeting the schedules of trunk or branch lines, the graphical chart often becomes rather complicated. The use of a large scale drawing, however, usually permits such a solution to be made with little difficulty. In fact such schedules have been very satisfactorily used with the varied types of service outlined above, but with the additional requirement that the train be made up of a varying number of cars controlled by the multiple unit system, the various cars being feeders to the trunk line from the branches

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en route and being joined together at the junction stations, thus forming the trains to enter the terminal city. The trains leaving the terminal city would operate in the reverse order, dropping car after car to the various branches and having relatively few through cars from terminal to terminal.

CHAPTER V.

MOTOR CHARACTERISTICS.

It will be readily recognized that the ordinary operation of a car, whether it be from block to block in the city or for a 5 or 10 mile run between stations on an interurban private right of way, may be subdivided into periods of acceleration, constant speed running, coasting deceleration, braking deceleration, and stop. The conditions of particular runs as to length, grades, curves, etc., may materially vary or even eliminate some of these periods, but if all problems of car operation are to be solved, a detailed study of each of these portions of the so-called "speed time curve" must be undertaken.

The principal factors entering into the determination of such a curve will be given detailed consideration in the following order, the present chapter dealing only with the first two functions.

Motor characteristics.
Gear ratio.
Weight of car.
Bearing and rolling friction.
Air resistance.
Rotative inertia of wheels and armatures.
Grades.
Curves.
Brake friction.

Motor Characteristics.—In studying the characteristics of motors, in order to determine those best fitted for traction service, it may be found convenient to classify all motors into the following types:

Direct Current:
- Series,
- Shunt,
- Compound,
  - Cumulative,
  - Differential.

Alternating Current, Polyphase:
- Induction,
- Synchronous.

Alternating Current, Single Phase:
- Series,
- Induction,
- Synchronous,
- Repulsion.

If the speed characteristics of all these motors be compared, it will be found that with varying loads within the rating of the motor the synchronous motors, both single and polyphase, maintain constant speed, while all the other direct and alternating current motors with the exception of the series type operate at nearly constant speed, the speed falling off slightly, usually in accordance with a straight line law, as the load increases. The speed characteristics of the compound motor may be made to approximate those of either the series or shunt motors by varying the relative strength of the series and shunt fields respectively. Since with constant potential motors, particularly of the direct current type, the current input to the motor varies approximately with the load, the speed-current curves of Fig. 10 may be taken as typical of the three classes of motors designed for commercial service. It should be noted that all of these motors maintain a speed of 400 r. p. m. at their rated load of 60 amperes, thus affording a basis for comparison.

The torque of a motor, which is defined as the tangential force that the armature is capable of exerting at a radius of 1 ft. from the center of the shaft, is proportional to the product of armature current and field strength. Since the field strength of a shunt type constant potential motor is constant, the torque varies directly with the armature current and approximately in proportion to the load. From the above reasoning, it would be expected that the torque of a series motor would vary with the square of the current since the field current and armature current are the same. In the actual design of series motors for railway service, however, the magnetic circuit is nearly at the point of saturation except at very light loads. The torque-current curve, therefore, while slightly concave upward at light loads, is nearly a straight

line for practically all operating current values since the field strength varies but slightly with change of current. In Fig. 11, a comparison of the torque-output curves of the three types of direct current motors will be found.

A study of the alternating current motors will reveal the fact that all types except the series have approximately the same inher-

SPEED CURVES OF REPRESENTATIVE TYPES OF MOTORS.

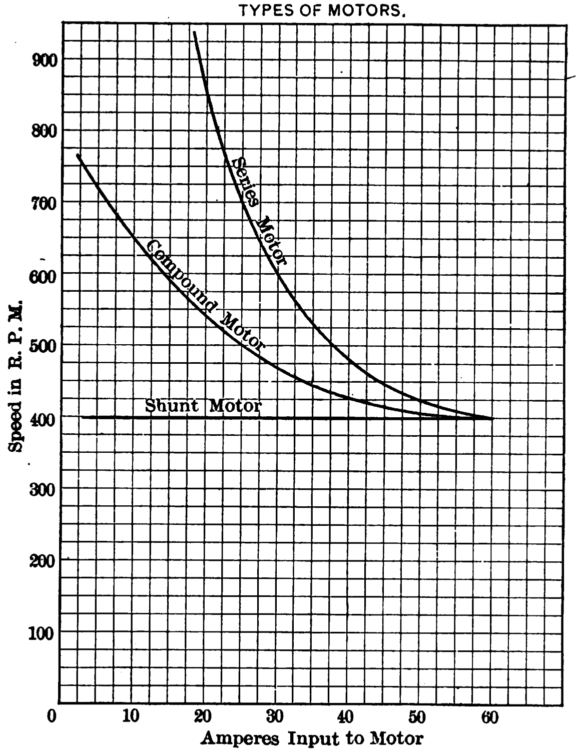


FIG. 10.

ent characteristics as the shunt type direct current motor, if the starting conditions of some of the former be disregarded. The series alternating current motor, as constructed at present for railway and hoisting service, has characteristics very closely approximating those of the series direct current motor.

In order to determine the best class of motor for traction purposes, therefore, it is only necessary to apply the characteristics

of typical shunt and series direct current motors to the conditions of railway service. Such characteristics may be found in Fig. 12 where A and A′ are the speed and torque curves of a series motor while curves B and B′ represent respectively the corre-

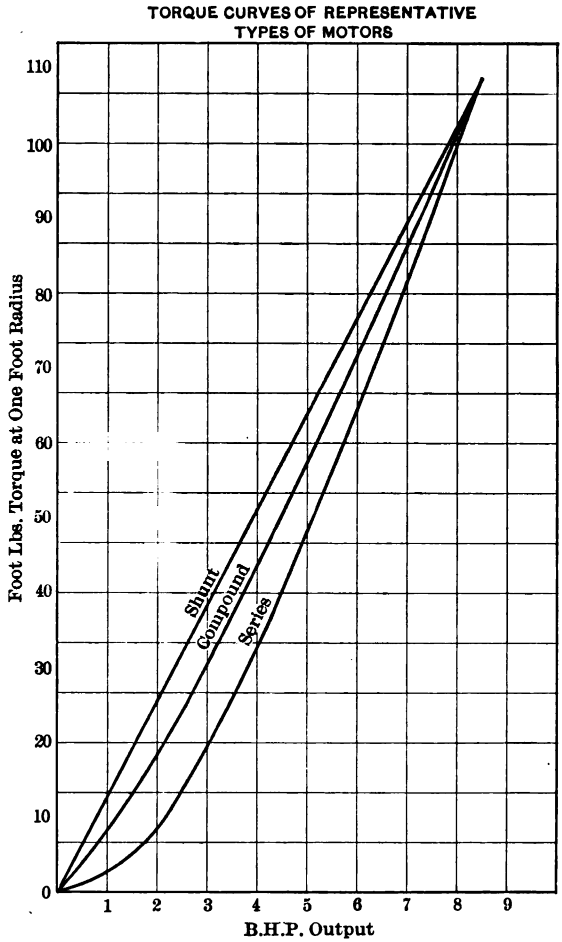


FIG. 11.

sponding characteristics of the shunt motor. The motors from which these characteristics were taken were designed for the common maximum speed of 22.8 m. p. h. with the particular gear ratio used. The torque is expressed in terms of "pounds

pull at periphery of car wheel" or "tractive effort" as explained under the section on "Gear Ratio."

It will be realized at once that a car under most conditions found in practice must be able to operate at variable speed. Conditions of grades, curves, pedestrian and vehicular traffic, necessary stops, etc., demand this. With the geared or direct

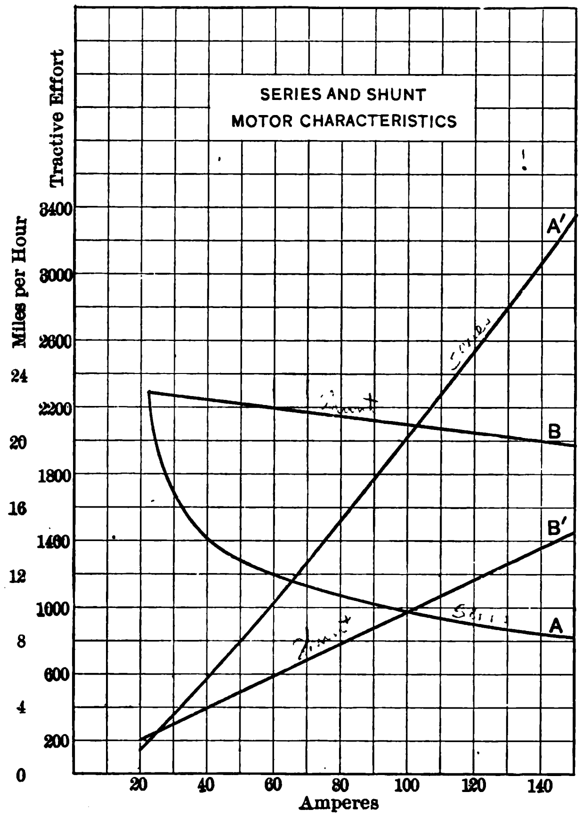


FIG. 12.

connection between motors and car axles usually adopted, therefore, a variable speed motor seems desirable. Furthermore, a much larger torque is required to start and accelerate a car than is necessary to maintain the car at full speed. As the power taken by a motor is roughly proportional to the product of torque and speed, if large values of torque cannot be obtained at low speeds

the power taken by the motor will be excessive. Reference to Fig. 12 will show that with the series motor a large torque is available at low speeds, the torque and the current as well falling off as the car accelerates and therefore as the demand for torque

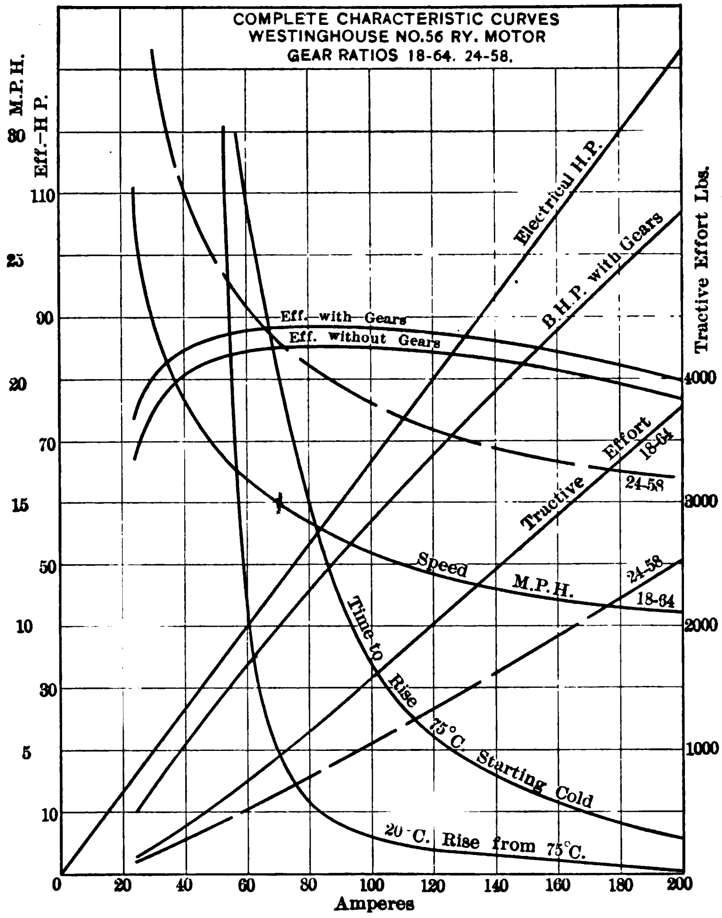


FIG. 13.

decreases. Assuming a concrete example, if a tractive effort of 1200 lb. per motor is required to accelerate a car the series motor of Fig. 12 will require but 68 amperes of current while the corresponding shunt motor will draw 125 amperes. Assuming

that they are both operating on the same line the power demand in the latter case will be nearly double that of the series motor.

For the above reasons the series direct current motor has come into almost universal use for traction service. During the last few years, however, the single phase series motor, with practically the same characteristics as the direct current series motor, has been installed in a number of instances. In several cases in Europe and in one instance in this country the polyphase induction motor has been adopted where conditions seemed to be particularly favorable for constant speed operation.

Confining the discussion to series motors, the characteristics already considered are the torque and speed curves plotted in terms of current input. To these should be added the curves of efficiency, often plotted both with and without gears, temperature rise, and, in the case of alternating current motors, the power factor. These characteristics, Fig. 13, may be obtained either from design data before the motor is built or by test after its completion.

Assuming that the design of a proposed motor has been tentatively made and its dimensions and winding data known, the speed, torque, and efficiency characteristics may be found as follows:

E = Impressed voltage.
e = Counter electromotive force.
I = Current in amperes.
T = Torque at 1 ft. radius in pounds.
R_a and R_f = Resistance armature and field respectively.
V = Speed in revolutions per minute.
N_a = Total conductors on surface of armature.
N_f = Turns on one field pole.
ϕ = Flux per pole in Maxwells.
p = Number of poles.
b = Number of paths in parallel on armature.
A = Area cross section magnetic circuit at air gap.
l = Length magnetic circuit.
μ = Equivalent permeability magnetic circuit.
W = Power delivered to the shaft of motor expressed in watts.

From the experimental definition of the volt:

$$e=\frac{N_a\phi pV}{60 \times 10^8 b} \tag{1}$$

or

$$V=\frac{60 \times 10^8 be}{Na\phi p} \tag{2}$$

but if leakage and armature reaction be neglected,.

$$\phi=\frac{4\pi N_f IA\mu}{10 l} \tag{3}$$

Simplified

$$V=\frac{47.7 \times 10^8 bel}{N_a pN_f IA\mu} \tag{4}$$

but

$$e=E-I(R_a+R_f) \tag{5}$$

therefore

$$V=\frac{47.7 \times 10^8 bl[E-I(R_a+R_f)]}{N_a pN_f IA\mu} \tag{6}$$

As all factors in the right hand side of equation (6) are either constants of the design or dependent upon current, a series of assumed values of current will give corresponding values of speed (V) from which the speed characteristic may be plotted. It will be seen from equation (2) that if (ϕ) be constant because of field saturation, the speed (V) will vary directly with the counter e. m. f. (e). Since, however, the voltage drop due to resistance is a small percentage of the impressed voltage, it may be said that the speed of a series motor varies with the voltage impressed upon it if load conditions remain the same. This fact is of importance in the design of car control systems.

With reference to the torque characteristic and neglecting iron losses,

$$W=eI \tag{7}$$

$$W=\frac{2\pi VT \times 746}{33000} \tag{8}$$

whence

$$T=\frac{33000\ eIN_a\phi p}{2\pi \times 746 \times 60 \times 10^8 be} \tag{9}$$

or

$$T=\frac{0.117\ IN_a\phi p}{10^8\ b} \qquad (10)$$

If the flux (ϕ) be assumed constant, which would be the case with the magnetic circuit saturated, equation (10) proves that the torque of a series motor will vary directly with the current as previously stated.

While the efficiency and temperature characteristics can be very closely approximated in advance by means of empirical formulæ, it is usually customary to determine these values roughly by comparison with other machines of similar design which have been previously constructed and to await the test for accurate results.

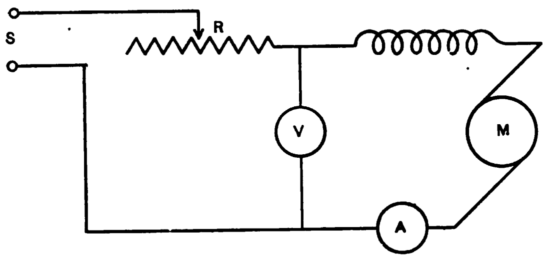


FIG. 14.

Several methods of testing are available for the determination of all the characteristics of the motor when constructed. Three methods will be briefly outlined, of which the one involving the apparatus most available may be selected.

Prony Brake Method.—This method is probably the simplest of the three and may be used where plenty of power is available for the operation of the motor up to 50 or 100 per cent. overloads. As the name implies, the motor is loaded by means of a prony brake from which the torque may be directly determined, while the current and speed are read directly by means of an ammeter connected in series with the motor at (A), Fig. 14, and a tachometer. The resistance (R) may be inserted, if necessary, to maintain constant voltage across the motor. The efficiency curve may be obtained by making a series of calculations from the

following formula (13) with varying currents. It is believed that the derivation of the formula is self explanatory.

If T′ represent torque at pulley at 1 ft. radius.

$$\text{Output (h. p.)} = \frac{2\,\pi V T'}{33000} \tag{11}$$

$$\text{Input (h. p.)} = \frac{EI}{746} \tag{12}$$

$$\text{Efficiency} = \frac{0.142\ VT'}{EI} \tag{13}$$

Pumping Back Method.—For this test two motors, identical in design and construction, are necessary, but the method has the advantage of a relatively small power demand as the losses alone are supplied from outside sources.

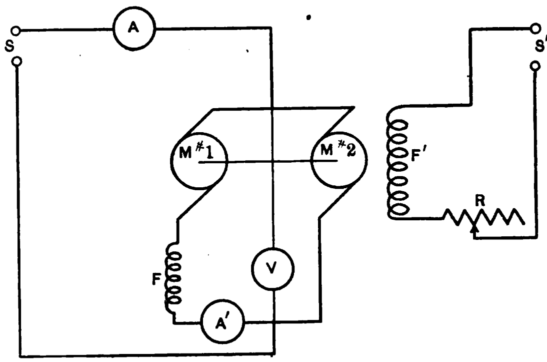


FIG. 15.

Two motors are placed in alignment with shafts end to end and mechanically clutched together. They are so connected, Fig. 15, that one machine, acting as a motor with a separately excited field, drives the other as a generator. The latter has a series connected field. By varying the field strength (F′) by means of the resistance (R) the current (A′) may be controlled from no load to overload. The output of motor No. 2, if the losses are supplied from the external source (S) is the product of the readings (V) and (A′). This value of power, reduced to foot pounds per minute and divided by 2π times the speed of the set, determines

the torque. Speed and torque plotted against current in amperes read from meter (A′) furnish the two principal motor characteristics.

In order to find the efficiency, for which a knowledge of the losses is necessary, the assumption is made that the combined iron and friction losses of the two machines are equal. Since the I^2R loss of No. 2 has been eliminated from the calculation by the fact of its separate excitation, the losses represented by the power (AV) must be made up of the following:

Friction losses of both machines.

Iron losses of both machines.

I^2R losses of both armatures.

I^2R losses of No. 1 field.

If the resistances of both armatures and fields are known, the I^2R losses can be readily calculated for the various values of current. These losses subtracted from (AV) leave the total iron and friction losses of the two machines, one half of which, according to the above assumption, is chargeable to each motor. Thus the losses and therefore the efficiency of the motor under test become known and the efficiency characteristic may be plotted. If a more detailed analysis of iron and friction losses is desired, additional tests with different connections must be made.[1]

The two temperature curves of Fig. 13 showing respectively the time required for the motor to rise 75° C. above the room temperature when starting cold and the time to rise 20° C. above the temperature of 75° C. for the various currents in the motor circuit, are of the greatest value in selecting the proper motor for a given service not only, but for determining the temperature rise corresponding to various overloads which the motor will usually be called upon to carry for short intervals of time. The values from which these curves may be plotted can best be obtained by actual test preferably with the connections of Fig. 15, separate runs being made, of course, for each value of current. Thermometers placed on the various parts of the machine during the run indicate when the desired temperature has been reached and the time for such rise may then be plotted against the constant value of current maintained during the test. Additional

[1] See "Experimental Electrical Engineering" by V. Karapetoff, pp. 406–407.

thermometers may be applied to determine the temperature of rotating parts at the end of the test and the hot resistance of the windings taken to determine by calculation the internal temperatures of the coils.

Motor Used as a Generator.—In this case the motors are mechanically clutched together as in the "pumping back" test, one being used as a motor to drive the other as a generator. The latter is loaded by means of a water rheostat as shown in Fig. 16. The calculations for losses and efficiency are very similar to those

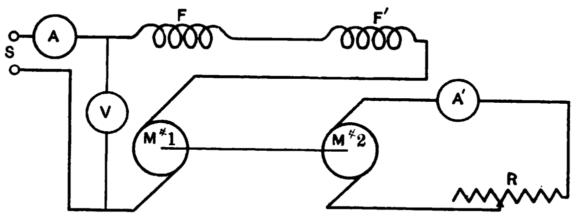


FIG. 16.

in the previous test, this method differing from the former principally in the type of load used. These connections are often used by the manufacturing companies for the one-hour heat run usually applied to railway motors.

Gear Ratio.—Since a suitable design for a railway motor demands a speed much higher than that at which the car axle should be driven in ordinary installations, single reduction gearing is introduced between the motor shaft and the car axle, a pinion upon the former engaging a gear keyed to the latter.

It has become customary in railway practice to express this gear ratio as an integer, or

$$\text{Gear Ratio} = \frac{\text{No. teeth in gear}}{\text{No. teeth in pinion}} \qquad (14)$$

As it is most convenient to plot the characteristic curves of railway motors in terms of forces at the periphery of the car wheel and speeds in miles per hour travelled by the car, it is obvious that a given group of such curves is dependent upon a single definite car wheel diameter and gear ratio. With a change of gear ratio, however, the motor speed remaining the same, the speed of the car will change in the inverse proportion while the

tractive effort will, of course, vary in direct proportion to the change in gear ratio.

The torque and speed characteristics may, therefore, be changed to apply to a new gear ratio by the use of the proportions given in equations (15) and (16).

$$\frac{\text{New Speed}}{\text{Old speed}} = \frac{\text{Old gear ratio}}{\text{New gear ratio}} \tag{15}$$

$$\frac{\text{New tractive effort}}{\text{Old tractive effort}} = \frac{\text{New gear ratio}}{\text{Old gear ratio}} \tag{16}$$

Motor characteristics thus changed are represented by the dotted lines of Fig. 13.

CHAPTER VI.

SPEED TIME CURVES (COMPONENTS.)

Weight of Car.—From the familiar relation Force = Mass x Acceleration expressed in the formula:

$$F = ma \tag{17}$$

it is clear that the weight of the car, complete with its equipment and load, will enter into the calculations for the speed time curve as an important factor. The above equation may, however, be reduced to a form more convenient for railway application as follows:

$$m = w/g \tag{18}$$

where (w) represents the weight in pounds and (g) the acceleration of gravity (32.2). Equation (17) becomes with this substitution

$$F = \frac{wa}{32.2} \tag{19}$$

Changing to the more convenient units of miles per hour in place of feet per second by means of the constant 1 m. p. h. $= \frac{5200}{3600} =$ 1.467 ft. per sec. or (a) = 1.467 A, when (A) is expressed in miles per hour per second and substituting 2000 W in place of (w) expressed in pounds equation (19) becomes

$$F = \frac{WA \times 2000 \times 1.467}{32.2} = 91.1\ WA \tag{20}$$

In order, therefore, to accelerate a car at a rate of 1 m. p. h. p. s., a net force of 91.1 lb. must be exerted for every ton weight of car. It must be remembered that this net force available for acceleration is only that which remains after all frictional resistances of the car have been overcome.

It is now possible to obtain a relation between the tractive effort of the motors comprising the car equipment and the acceleration

that this tractive effort will produce for a given weight of car. This will obviously depend upon whether a two or four motor equipment is used. Equation (20) may be written

$$A = \frac{p_m n}{91.1\,W} \tag{21}$$

if n = Number of motors on car

p_m = Net tractive effort per motor.

From the above equation it will be seen that the acceleration is inversely proportional to weight of car.

Bearing and Rolling Friction.—In studying the various retarding forces which have to be overcome by the motors in car operation and which must, therefore, be subtracted from the gross tractive effort of the motors in order to determine the net effort available for acceleration, it seems logical to consider first those forces acting under the normal conditions of a straight level track. Among these forces are found the friction of armature and axle bearings. The axle friction, which is usually the greater of the two, varies with the pressure on the bearing, and therefore with the weight of the car for a given truck arrangement. Both frictional resistances vary very nearly in proportion with the speed. In building up an empirical formula for train resistance, therefore, expressed in pounds train resistance per ton weight of car, it would be expected that bearing friction would be represented therein by a constant term added to a term varying with speed.

There are found to be present, however, in the operation of a car other frictional forces exerted between the wheels and rails. These forces have been termed "rolling friction." They are caused partly by the rubbing of the wheel flange against the head of the rail and partly by the fact that there is apparently a slight depression in the rail under each wheel out of which the wheel must be forced against an appreciable resistance. This effect is more marked with a greater distance between ties or in cases where rail spikes have become loosened, allowing considerable vertical motion to the rail as the car passes over it. Since the flange friction previously mentioned is considerably increased if the track gauge is not maintained constant, the entire item of rolling friction may vary greatly with the condition of the track. As

this resistance will also vary with the speed and weight of the car for a given track, both bearing and rolling friction may be represented by a single constant plus a second term varying with speed.

Air Resistance.—The amount of resistance offered to the motion of the car by the air is very surprising, especially in the case of single cars at relatively high speeds. Not only is there considerable resistance offered to the front cross section of the car as it cuts through the various strata of air but the friction of the air upon the sides of the car and the eddies and suction produced at the rear cause a considerable retarding effect upon the motion of a train. This suction phenomenon may readily be observed at the rear of a high speed train by noting the motion which it conveys to cinders and light objects found along the track.

This air friction upon the various portions of the car has been more or less successfully measured in train resistance tests, but there still exists a wide difference of opinion regarding its absolute value. It is generally conceded, however, that the front and rear end resistances are proportional to the cross-sectional area of the car from car axle to roof and that the side resistance of a single car is approximately one-tenth of the sum of head and rear resistances. Since the side resistance is much smaller than the end resistance it would be expected that the total air resistance per ton weight of car would be very much greater for a single car than for a train. This has been found to be so marked in the tests carried out that it is usually impractical to operate a single car much over 60 m. p. h., while a train of many cars may be operated at much higher speeds without serious loss. While this air resistance is a comparatively small quantity at low speeds, it is generally considered to vary with the square of the speed and is therefore a very formidable factor at high speeds.

As a result of the various train resistance tests which have been made by determining the deceleration of cars and trains while coasting from different initial speeds to a standstill on a straight level track, a number of empirical formulæ have been suggested and used with varying degrees of accuracy in train calculations. The tests which have been made comparatively recently with electric equipment, with which the power is much more accurately measured than in steam locomotive tests, may be represented by

the curves of Fig. 17, plotted in pounds per ton train resistance for 25 ton cars against speed in miles per hour. This train resistance includes bearing and rolling friction and air resistance upon the entire car or train.

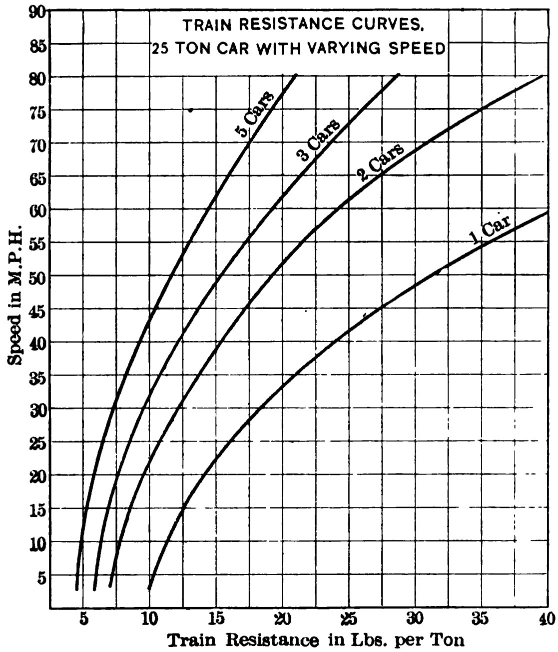


FIG. 17.

The empirical formula from which these curves were plotted and which probably approximates most closely the true train resistance in practice is represented below.

$$^{1}R = \frac{50}{\sqrt{W}} + .03V + \frac{.002}{W} V^2 a \left(1 + \frac{n-1}{10}\right) \qquad (22)$$

R = Total train resistance in pounds per ton weight of train.

W = Weight of train in tons.

V = Speed of train in miles per hour.

a = Area of cross section of front end of car or locomotive above axle expressed in square feet.

n = Number of cars in train.

[1] See "Electric Traction" by A. H. Armstrong.

In this formula the first two terms express the rolling and bearing friction while the last term determines the resistance due to air friction and suction.

The effect of increased weight of cars upon train resistance at constant speed is very clearly shown in the curves of Fig. 18, which are plotted from the same formula. It must be remembered that this effect is entirely separate from the extra tractive

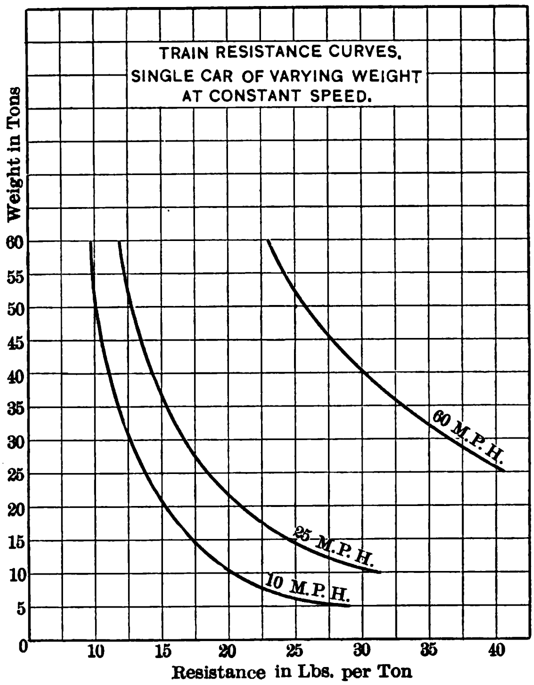


FIG. 18.

effort necessary to accelerate the heavier cars and therefore represents an additional negative force or resistance which the motors are called upon to overcome when operating heavy rolling stock.

Rotative Inertia of Wheels and Armature.—It will be remembered from mechanics that if two different rotating masses of different inertia are acted upon by similar propelling and similar resisting forces respectively, the mass having the greater in-

ertia will have the lower value of acceleration or decleration as the case may be.

From this fact it would be expected that the relatively large inertia of the rotating elements of the car, including motor armatures, gears, pinions, axles, and wheels would tend to reduce the acceleration when the car is starting and the deceleration when coasting and braking. This inertia factor must be taken into consideration in the accurate calculation of speed time curves as follows:

The energy of rotation—

$$E=\frac{\omega^2 I}{2}=\frac{M\omega^2 k^2}{2} \tag{23}$$

since

$$I=Mk^2 \tag{24}$$

where ω = Angular velocity,

I = Moment of inertia,

M = Mass,

k = Radius of gyration.

These fundamental formulæ will be applied to this particular problem with the following nomenclature:

n_w = Number of pairs of wheels on car.

n_a = Number of armatures on car.

W_w = Weight of each pair of wheels and axle in tons.

W_a = Weight of each armature in tons.

k_w = Radius of gyration of wheels and axle.

k_a = Radius of gyration of armature.

r = Radius of wheels in feet.

A = Acceleration of car in m. p. h. /sec.

V = Velocity of car in m. p. h.

v = Velocity at extremity of radius of gyration.

g = Acceleration of gravity.

G = Gear ratio.

W = Weight of car in tons.

p = Net tractive effort at periphery of wheel.

Considering first the wheels and axles:

From equation (23)

$$E_w=\frac{n_w W_w (k_w \omega)^2}{2g} \tag{25}$$

But

$$k_w \omega = v \tag{26}$$

Substituting

$$E_w = n_w \frac{W_w v^2}{2g} \tag{27}$$

Since the velocity of the periphery of the car wheel is the same as that of the car, if it be assumed that no slipping occurs,

$$E_w = n_w \frac{W_w}{2g} \left(\frac{k_w}{r} V \right)^2 \tag{28}$$

or, in other words, replace $n_w W_w$ with the equivalent weight $\left(\frac{k_w}{r} \right)^2 n_w W_w$ if (V) is used in (27).

In a similar manner, remembering that in transferring armature values to those at the periphery of the wheel the gear ratio (G) must be introduced,

$$E_a = n_a \frac{W_a}{2g} \left(\frac{k_a}{r} GV \right)^2 \tag{29}$$

from which the equivalent weight is $\left(\frac{k_a}{r} G \right)^2 n_a W_a$.

By adding the new values of equivalent weight, expressed in tons, necessary to overcome rotational inertia, therefore, formula (20) may be corrected to read

$$F = 91.1\ A \left[W + n_w W_w \left(\frac{k_w}{r} \right)^2 + n_a W_a \left(\frac{k_a G}{r} \right)^2 \right] \tag{30}$$

Since the radius of gyration

$$k = \sqrt{\frac{I}{M}} \tag{31}$$

and all revolving parts to be considered in electric traction are cylinders revolving about their axes,

$$I = M \frac{r^2}{2} \tag{32}$$

$$k = \frac{r}{\sqrt{2}} \tag{33}$$

In order to determine approximately the magnitude of the inertia of rotating parts the following concrete values, which are often found in practice may be assumed.

$$n_w = n_a \qquad = 4$$
$$W_w = 1500 \text{ lb.} \qquad = 0.75 \text{ ton.}$$
$$W_a = 700 \text{ lb.} \qquad = 0.35 \text{ ton.}$$
$$r = \frac{33 \text{ in.}}{2 \times 12} \qquad = 1.375 \text{ ft.}$$
$$k_w = \frac{33 \text{ in.}}{2 \times 12\sqrt{2}} \qquad = 0.97 \text{ ft.}$$
$$k_a = \frac{14 \text{ in.}}{2 \times 12\sqrt{2}} \qquad = 0.412 \text{ ft.}$$
$$A = 1 \text{ m. p. h./sec.}$$
$$G = 19/52 \qquad = 2.74$$
$$W = 25 \text{ tons.}$$

Substituting in (30)

$$F = 91.1\ (25 + 1.49 + .944) = 2500 \text{ lb.}$$

or 100 lb. per ton. In other words, the net tractive effort necessary for translation must be increased approximately 9.8 per cent. for this car in order to overcome the inertia of rotating parts for an acceleration of 1 m. p. h./sec.

For approximate calculations, 100 lb. per ton is often assumed for the net tractive effort without calculation of rotative inertia. The following table taken from the Standard Handbook will give other values which may be assumed under varying conditions.

TABLE V.

PER CENT. OF TOTAL TRACTIVE EFFORT CONSUMED IN ROTATING PARTS.

Electric locomotive and heavy freight train	5 per cent.
Electric locomotive and high speed passenger train	7 per cent.
Electric high speed motor cars	7 per cent.
Electric low speed motor cars	10 per cent.

Grades.—Whenever a grade is encountered it is not only necessary to provide an additional tractive effort to overcome

linear and rotational inertia, but it is also necessary to make use of some of the tractive effort of the motors in actually lifting the car through the vertical distance represented by the grade. In other words, referring to Fig. 19, the weight of the car (W) may be resolved into the two forces (N) and (W sin a) which are

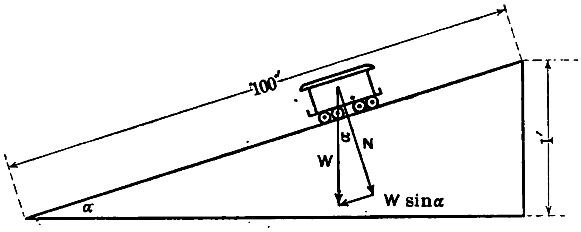


FIG. 19.

normal and parallel to the track respectively. The reaction of the track balances the former while a force proportional to the latter must be supplied by the motors of the car. As the angles (α) and (α') are equal it is obvious that this force is proportional to the grade and amounts to 0.01 x 2000 = 20 lb. per ton weight of car for each per cent. of grade. If the car is on a down grade

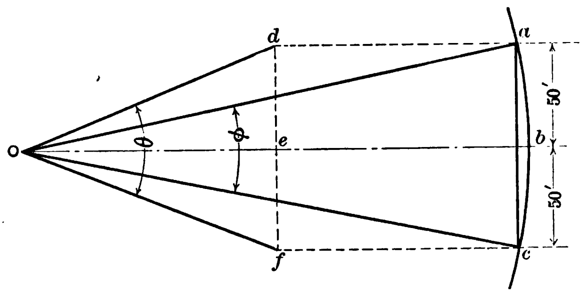


FIG. 20.

this force is available for producing acceleration and is therefore added to the tractive effort of the motors.

Curves.—Before it is possible to consider the resistance offered to the passage of a car or train by curves in the track, it is necessary to understand clearly the method of rating curves. In city streets where sharp curves are met with, they are usually desig-

nated by their radii, *e.g.*, a curve of 30 ft. radius. On private rights of way, however, in suburban and interurban construction it has been customary to designate curves in degrees of central angle subtended by a chord of 100 ft. Referring to Fig. 20, if angle (ϕ) is drawn so that it is subtended by the chord (ac) of 100 ft. and $(\phi)=1°$, then the radius (Ob) necessary to make this assumption correct is found as follows:

$$\tan 30' = .0087 = \frac{50}{(Ob)} \text{ or } (Ob) = 5730 \text{ ft.}$$

The radius of a 1° curve is therefore 5730 ft.

If now (ab) be moved toward (O) such a distance as to make $(Oe)=(eb)$

$$\tan \frac{\theta}{2} = \frac{50}{2865} = .0175 = \tan 1° \text{ or } \theta = 2°.$$

Therefore, curvature in degrees $= \dfrac{5730}{\text{radius}}$.

As a car enters a curve there is, of course, a tendency to ride over the outer rail and there occurs between the flange of the car wheel and the head of the rail considerable frictional force tending to cause the car to follow the rail but at the same time retarding the motion of the car. This force must be considered as an additional resistance which manifests itself in frictional heat.

The amount of this resistance has been approximated from test data and it is conceded that it is directly proportional to the curvature in degrees. Values ranging from 0.52 lb. to 1 lb. per ton weight of car per degree curvature have been obtained but good practice at present stipulates 0.6 lb. per ton weight of car per degree curvature. When the car is on a curve, therefore, an additional force of 0.6 W x degrees curvature must be subtracted from the gross tractive effort in addition to all resistances previously considered.

Probably the best method of summarizing the discussion of train resistance is to express in terms of a formula the derivation

of the net tractive effort available for acceleration from the gross tractive effort obtained from the motors, thus—

$$p = P - f \pm g - c \tag{35}$$

where

P = Gross tractive effort of motors in pounds per ton.

p = Net tractive effort available for acceleration in pounds per ton.

f = Train resistance due to bearing and rolling friction and air resistance in pounds per ton.

g = Resistance due to grades in pounds per ton.

c = Resistance due to curves in pounds per ton.

The use of this net tractive effort (p) in calculating the acceleration of a car or train will be discussed in detail in the following chapter.

CHAPTER VII.

Speed Time Curves (Theory).

Having considered in detail the various factors entering into the speed time curve, the methods of plotting same may now be considered. Two methods are in general use, the so-called "cut and try" method which involves considerably more time for its performance but which is the more accurate, and the "straight line" method which assumes all portions of the diagram made up of straight lines, thereby simplifying the calculation at the expense of the introduction of slight errors. The former and more accurate method will first be considered, for only through the complete analysis of the correct curves can a thorough understanding of electric car performance be obtained.

The distance between the two consecutive stops having been determined, it is next necessary to select the proper schedule speed for the run, *i.e.*, the average speed, which if maintained constant throughout the run would bring the car to its destination in the required time. This speed is usually determined from traffic studies, and is, of course, dependent upon the train schedule of the entire system. With the distance and schedule speed determined, the time required for the run can be calculated and the limits of the curve laid off graphically to scale as (OT) in Fig. 21.

The nomenclature which will be used is as follows:

T.E. = Gross tractive effort per motor in pounds.
P = Gross tractive effort at periphery of car wheel in pounds per ton.
p = Net tractive effort in pounds per ton.
v = Speed corresponding to (TE) in m. p. h.
I = Current corresponding to (TE) in amperes.
A = Acceleration in m. p. h./sec.
D = Deceleration in m. p. h./sec

V = Schedule speed in m. p. h.
S = Length of run in feet.
s s′, etc. = Distances in feet.
T = Time for entire run in seconds.
t, t′, etc., = Time for portions of run in seconds.
f = Train resistance in pounds per ton.
g = Grade resistance in pounds per ton.

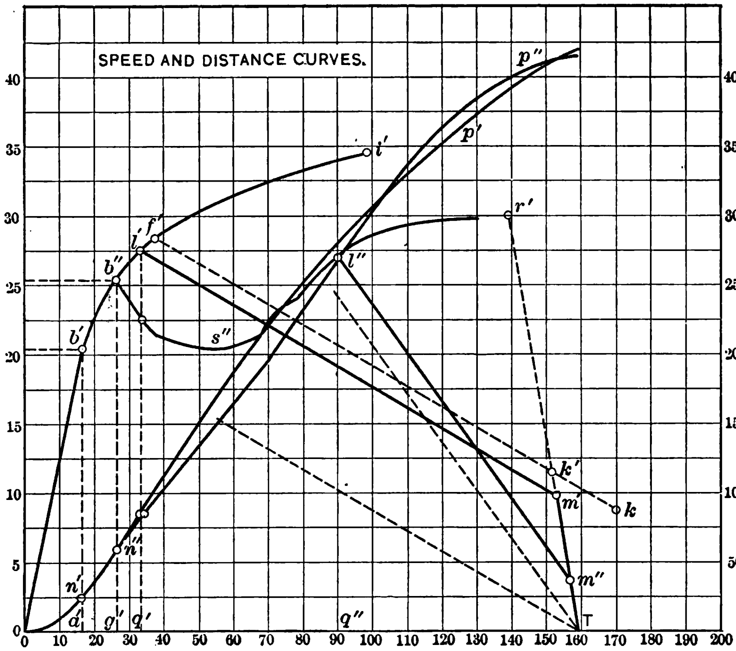


FIG. 21.

c = Curve resistance in pounds per ton.
b = Braking resistance in pounds per ton.
W = Weight of car in tons.
n = Number of motors on car.
W_1 = Weight of car per motor in tons.

Referring to Fig. 21.

$$OT = T = \frac{S}{V \times 1.467} \tag{36}$$

The acceleration (A) must be assumed sufficiently large to

enable the desired schedule to be made and yet not so great as to be of inconvenience to passengers. The method of calculating the net tractive effort (p) has been previously explained in formulæ and it will therefore be considered as a known quantity.

The gross tractive effort per ton may now be found

$$P = (p + f \pm g + c) \tag{37}$$

The sign of the grade resistance (g) depends, of course, upon whether the car is ascending or descending the grade; in the latter case the sign is negative and the gross tractive effort necessary is decreased by the presence of the grade.

The weight of car which must be accelerated by each motor is:

$$W_1 = \frac{W}{n} \tag{38}$$

The gross tractive effort which the motor must exert is therefore:

$$T.E. = PW_1 = \frac{W}{n}(p + f \pm g + c) \tag{39}$$

Referring to the characteristic curves of the motor which has been assumed as probably of the correct design for this service the gross tractive effort (T.E.) is found to correspond to a current I (Oa, Fig. 22) and at this current the speed is v (ab, Fig. 22). The motors of the car will be able to maintain this rate of acceleration (A) as long as they can be supplied with current $I = Oa$. As the speed increases, however, the current and therefore the tractive effort will decrease unless the voltage applied to the motors is increased. This is the function of the control equipment whether it be of the rheostatic, series parallel, or auto-transformer type. Until such time as the voltage impressed upon the motors reaches the maximum value possible with the particular control equipment in use the assumed value of acceleration (A) may be used for calculation. In other words the acceleration portion of the speed-time curve may be drawn as a straight line from O with a slope of $\left(\frac{dv}{dt} = A\right)$ until a speed is reached corresponding to $(v = ab)$, Fig. 22. This line is drawn as Ob′ in Fig. 21 where $a'b' = ab$, Fig. 22.

Beyond the point (b′) the "cut and try" method using incre-

ments of speed and time must be used. The time, t = Oa′ corresponding to point b′, can readily be calculated from the equation

$$t = \frac{V}{A} = \frac{a'b'}{A} \tag{40}$$

Assuming a small increment of speed beyond point (b′) = dv, the new speed is (v + dv) = ec. Referring to the characteristic

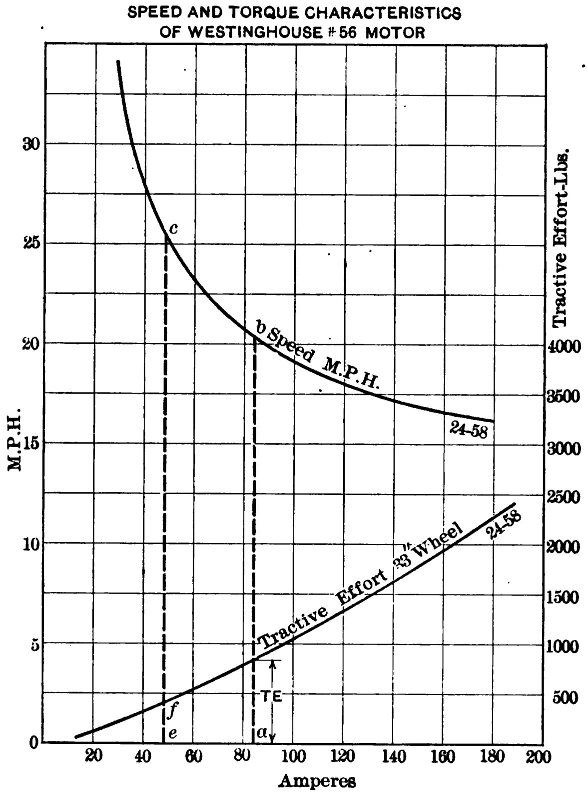


FIG. 22.

curves (Fig. 22), this speed (ec) corresponds to a gross tractive effort T.E.′ = (ef). It is now necessary to determine what acceleration this tractive effort can produce as follows:

Net tractive effort $$p' = \frac{T.E.'}{W_1} - f' \pm g' - c' \tag{41}$$

If the speed increments are selected sufficiently small the value of (f′) will not be materially different from (f), although for accurate work substitution should be made of the resistance from the train resistance curves, Fig. 17, for the average speed represented by the increment (dv). The distance curve explained below will determine the portions of track corresponding to various points on the speed time curve, thus permitting correct values of (g) and (c) to be selected. In many cases these latter values do not change materially throughout the calculation.

Having determined the new value of net tractive effort (p′)

$$A' = \frac{p'}{p}A \tag{42}$$

where (A′) is the new acceleration for the increment of speed (dv). The time required to traverse the distance (ds) may be calculated from the equation

$$dt = \frac{dv}{A'} \tag{43}$$

The coordinates of the next point upon the acceleration curve are therefore known to be $(v+dv)=g'b''$ and $(t+dt)=Og'$ and the point may therefore be plotted as (b″).

If this procedure be continued, assuming new increments of speed and calculating the corresponding values of the time increments, the complete acceleration curve may be plotted. This curve will become horizontal when the acceleration reaches zero; or, in other words, when the gross tractive effort of the motors is completely balanced by the resistances so that no net tractive effort remains to produce acceleration. With no change in grade or curvature of track the car will continue running at constant maximum speed until the power is shut off.

Coasting.—The amount of coasting permissible in a given run varies widely. In some instances where schedules are very conservatively planned and the equipment more than adequate for the demands made upon it, excessive coasting is introduced, while in heavy suburban and elevated service, braking is often begun as soon as power is shut off, the coasting portion of the curve being entirely eliminated. In order to be able to make up time in case of delay, however, some coasting should be provided

for in the speed time curve, the time involved in this portion of the run acting as a storage reservoir for a hydraulic plant since it may be drawn upon if necessary to maintain normal schedules.

In order to plot an absolutely accurate coasting curve the "cut and try" method should be used, since the average speed during the coasting period, from which the train resistance factor (f) is obtained, is difficult to predetermine and for the further reason that the resistance (f) does not vary directly with the decrease in speed. It is customary, however, to consider the coasting portion of the diagram as a straight line, *i.e.*, to assume the deceleration constant, and to select the value of (f) from appropriate resistance curves (Fig. 17) for an approximate average speed during coasting, or even to assume (f) directly. This value is often taken arbitrarily at 15 lb. per ton.

With the value of (f) known, the deceleration is

$$D_c = \frac{-(f \pm g + c)}{p} A \qquad (44)$$

from which the increment of time (dt) corresponding to an assumed change of speed (dv) may be calculated as follows:

$$dt = \frac{dv}{D_c} \qquad (45)$$

The coasting line may then be drawn through (f′), Fig. 21, with a slope $D_c = \frac{dv}{dt}$. Such a line is (f′k), Fig. 21 (f′), being any point arbitrarily selected upon the acceleration curve. The line (f′k) determines the direction but not necessarily the exact position of the coasting line.

Braking.—Since the speed time curve must cut the time axis at T, Fig. 21, in order that the run may be completed in the predetermined schedule time, the braking line can best be drawn back from T, the slope being determined by the assumed braking deceleration as in the case of the coasting curve. As in the case of acceleration this rate must be selected sufficiently high to enable the schedule to be maintained and yet not prove disagreeable to passengers. In heavy suburban and elevated traffic where speed

is relatively high and headway short the braking rate must necessarily be high. An average figure often assumed is 1.5 m. p. h. /sec. The braking line in Fig. 21 is represented by Tr′.

The area under the speed time curve obviously represents the distance travelled during the run. In plotting the curve, therefore, especially if the distance time curve is not simultaneously plotted, it is advisable to determine the area of the diagram occasionally by means of a planimeter as a check upon the distance. In closing the diagram, also, after the braking line has been drawn, the coasting line (l′m′) must be so located parallel to (f′k) that the area of the diagram will correspond to the distance travelled between the stops under consideration. The completion of the diagram is therefore a "cut and try" method.

In order that this method of plotting speed time curves may be more clearly understood a concrete example of a typical problem will be found in Chapter IX.

CHAPTER VIII.

Distance, Current, and Power Time Curves (Theory).

The speed time curve having been determined, the secondary curves which are dependent thereon may now be given consideration.

Distance Time Curves.—The distance time curve which is usually plotted simultaneously with the speed time curve is also obtained by the "step by step" method, the series of increments of time determined for the speed time curve together with the corresponding average speeds during the increment being used to calculate the increments of distance as follows:

$$ds = \frac{v_1 + v_2}{2} \times 1.467\ dt \qquad (46)$$

These increments of distance when plotted form the curve (On′p′), Fig. 21, having ordinates expressing distance in feet corresponding to abscissæ of time in seconds. Such a curve rises slowly as the speed increases, maintains a constant slope, and gradually approaches the horizontal during the coasting and braking periods.

Current Time Curve.—In order that the power which will be taken by a car on a given run may be predetermined the current and voltage time curves must be plotted. Since the voltage is usually assumed constant at some average value which may reasonably be expected to obtain over the entire line its graphical representation is merely a straight horizontal line.

With the current, however, it will be remembered that the control equipment is expected to maintain practically constant current values in each motor until the net tractive effort falls below that necessary for the initial assumed acceleration. This point, which is represented by (b′), Fig. 21, has its time coordinate definitely fixed. The current per motor (I), as found from

the characteristics for this particular speed might be plotted as constant from the start to a point (t = oa'). Since, however, the series parallel control is ordinarily used and the current consumption for two motors is the important consideration, it is usually assumed that during the first half of the time (oa'), Fig. 21, the motors are in series and during the latter half period in parallel. The current consumption for two motors is, therefore, double the value in the latter or parallel half that it is in the first or series half of the constant acceleration portion of the run.

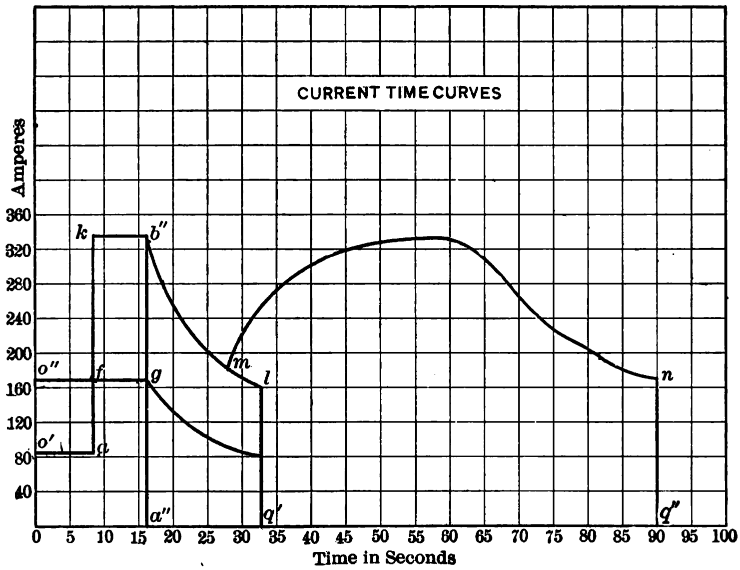


FIG. 23.

Thus two of the motors of a four motor equipment would have a current-time curve during the constant acceleration period represented by (OO'afg), Fig. 23, while the current of all four motors or better, the current per car for the same period may be determined at any instant from the curve (OO''fkb'') of the same figure. Since the two sets, of two motors each, are in parallel with each other the total current per car in the series connection (OO'') is double (OO') and the corresponding "parallel" current (a''b'') is double (OO'').

Beyond the point b'', because of the increase of speed, the

current begins to decrease, each point on the curve being readily determined by referring back to the motor characteristic curve, Fig. 22, for the current values corresponding to the various coordinates of speed and time on the speed time curve. The complete current curve up to the time (oq′), Fig. 21, where the current is shut off, may then be plotted as (OO″fkb″lq′), Fig. 23.

Power Time Curve.—The power taken at various times during the run can be very readily represented graphically with

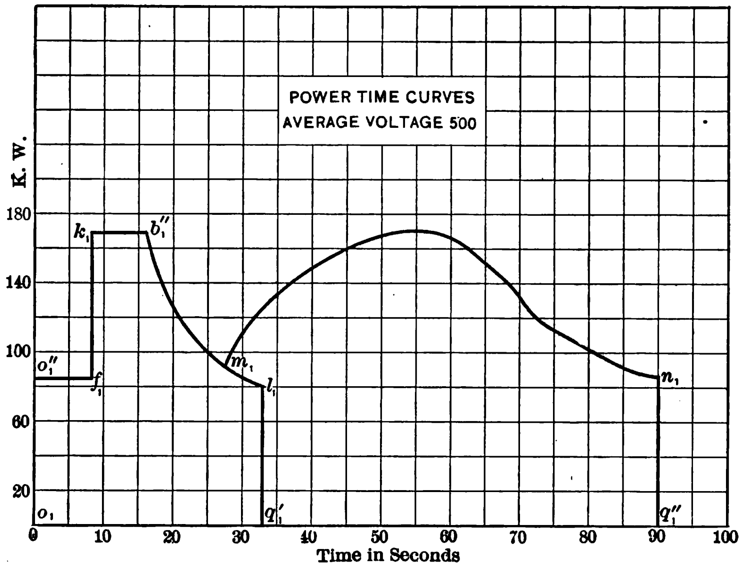


FIG. 24.

the same abscissæ as the above current curve but with ordinates which are the products of the current curve ordinates and the average assumed voltage. Since the voltage is constant, the power diagram ($O_1O_1''f_1k_1b_1''l_1q_1'$), Fig. 24, will take the same form as the current curve.

If alternating current series motors are being considered, with which the series parallel control is seldom used, the current per motor and also per car will remain fairly constant throughout the constant acceleration period, *i.e.*, during the time (Oa″), Fig. 23. Since the voltage impressed upon the motors during this period is

usually varied by means of an auto-transformer or induction regulator, neither of which involve the power losses incurred by the direct current rheostatic and series parallel control systems, the voltage curve is assumed as a straight line between the starting voltage and maximum operating secondary voltage. This starting voltage, or the voltage necessary to produce the initial tractive effort may be determined from motor tests while the maximum operating secondary voltage is usually that at which the motors are designed to operate.

If the product of the ordinates of the current and voltage curves for each of the time increments be plotted to a scale reduced

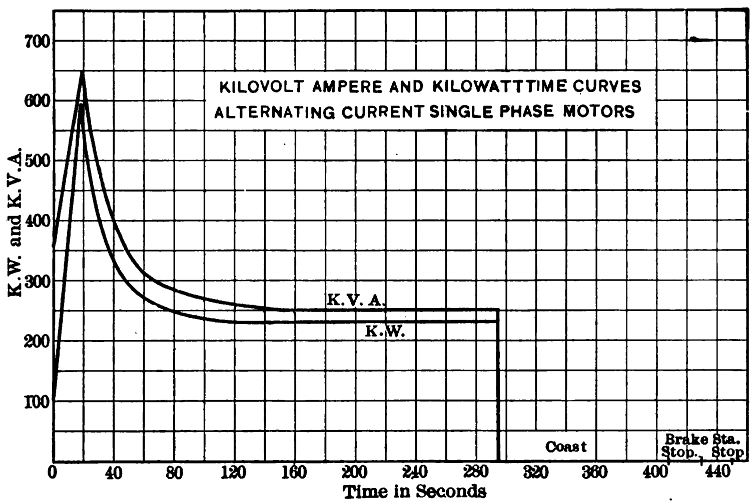


FIG. 25.

in the ratio of 1000 to one, a kilovolt-ampere curve results which is quite as useful in determining substation and distribution system requirements as the kilowatt-time curve. Fig. 25 illustrates such a kilovolt-ampere curve for a proposed interurban line operating 72 ton, 2 car trains, made up of a 44 ton motor car and a 24 ton trailer with rotative weight of 4 tons, equipped with four 125 h. p., 200 volt, 25 cycle single phase alternating current series motors with a 2.33 gear ratio.

Whereas the kilovolt-ampere time curve is of great value as explained above, it is usually necessary to know the actual power

consumption expressed in kilowatts at any time during the run. This is rendered possible by plotting the kilowatt-time curve, Fig. 25, which is related to the kilovolt-ampere curve at any instant by the expression

$$\text{Kilowatts} = \text{Kilovolt-amperes x power factor} \qquad (47)$$

Reference to Fig. 99, will show that the power factor of an alternating current railway motor varies with the current. In order to fix accurately a point on the kilowatt time curve of Fig. 25, therefore, it is necessary to select a given instant of time, find the current in the motor at that instant from the current-time curve, determine the corresponding power factor from the motor characteristic curve and substitute in equation (47). In many cases, however, it will be found sufficiently accurate to assume an average power factor for the entire curve with the possible exception of the starting value which is usually considerably lower than the average operating power factor.

The area enclosed by a kilowatt-time curve is a measure of the energy consumed by the car or train during the run, thus,

$$E = \frac{\text{Area of diagram}}{3600} \qquad (48)$$

$$E_1 = \frac{\text{Area of diagram x1000x5280}}{3600\ WS} \qquad (49)$$

where

E = Energy in kilowatt hours.

E_1 = Energy in watt hours per ton mile.

W = Weight of car or train in tons.

S = Length of run from station to station in feet.

If this energy be expressed in kilowatt hours (E) it will be found to be in convenient form for calculating substation demands, while if expressed in "watt hours per ton mile" (E_1) it will be found useful in comparing various runs with different types of equipment and under different service conditions, since it has become customary to express the results of power-time curve calculations for the purpose of simplicity in terms of this unit.

CHAPTER IX.

Speed Distance, Current and Power Curves (Concrete Examples).

In order that the use of the formulæ and the method of plotting curves outlined in the previous chapters may be thoroughly understood, a typical concrete problem will be considered. Although this particular case has been considered because of its rather exceptional changes in grade, involving the most difficult phase of the problem, the curves will first be plotted using the distances listed in Table VI, but assuming the track a level tangent. Comparative curves will later be calculated and plotted to illustrate the effect of grades.

TABLE VI.

Distances and Grades of Typical Run.

Street crossings.	Grade (per cent.).	Distance from last stop (feet).	Distance from start (feet).
A to B..........	0.0	600	600
B to C..........	6.0	880	1480
C to D..........	5.0	400	1880
D to E..........	2.0	320	2200
E to F..........	0.5	1240	3440
F to G..........	1.0	760	4200

A 25 ton interurban car, equipped with four Westinghouse No. 56, 50 h. p., d. c. railway motors and series parallel control, is to be operated over this road at a schedule speed of 18 m. p. h. The characteristics of this type of motor are found in Fig. 13.

The initial constant acceleration will be assumed as 1.25 m. p. h. p. s. which is a fairly representative figure in electric railway practice.

A force of 100 lb. per ton will be considered as the necessary tractive effort to overcome the inertia of both translation and rotation in accelerating the car at a rate of 1 m. p. h. p. s. The resistance curves found in Fig. 17 are plotted for a car of this weight and will therefore be used in this problem.

The values which must be substituted for the symbols listed in Chapter VII, page 59, are therefore as follows:

$p = 125.$
$A = 1.25.$
$V = 18.$
$S = 4200.$
$W = 25.$
$n = 4.$
$W_1 = 6.25.$

Using formula (36) the time of run is

$$T = \frac{4200}{18 \times 1.467} = 159 \text{ seconds.}$$

In order to substitute in formula (37) for gross tractive effort the value of train resistance (f) must be approximated. This may be done sufficiently accurately by selecting the value from Fig. 17 corresponding to the average speed which must be assumed for the constant acceleration period.

Taking this average speed at 10 m. p. h. (f) = 11 lb. per ton. From equation (37)

$$P = (125 + 11) = 136 \text{ lb. per ton.}$$

The gross tractive effort is therefore:

$$T.E. = 6.25 \times 136 = 850 \text{ lb.} \tag{39}$$

Referring to the characteristic curves of this motor, Fig. 13, the current and speed for this tractive effort are:

$I = 84$ amp.
$V = 20.4$ m. p. h.

The average speed from the start is therefore 10.2 m. p. h. which proves the assumption of 10 m. p. h. used in obtaining the value of train resistance (f) was sufficiently accurate. Had this assumption been much in error a corrected calculation of tractive effort should have been made.

The time required for the period of constant acceleration is calculated from formula (40)

$$t=\frac{20.4}{1.25}=16.3 \text{ seconds.}$$

The line (Ob′), Fig. 21, may now be plotted.

The corresponding distance covered is

$$s=O+\frac{20.4}{2}\times 1.467\times 16.3=244 \text{ ft.} \tag{46}$$

This determines one point (n′) on the distance curve.

In order to determine the first point (b″) on the curved portion of the acceleration diagram, an increment of speed must be assumed.

Let dv = 5 m. p. h. or v + dv = 25.4 m. p. h.

The gross tractive effort on the characteristic curve corresponding to 25.4 m. p. h. is

T.E. = 400 lb.

The average speed for this increment being 22.9 the new value of train resistance (f′) will be found from the resistance curves to be

f′ = 15 lb. per ton

The new value of net tractive effort is therefore

$$p'=\frac{400}{6.25}-15=49 \text{ lb. per ton.} \tag{41}$$

The corresponding value of acceleration is

$$A'=\frac{49}{125}\times 1.25=0.49 \text{ m. p. h. p. s.} \tag{42}$$

$$dt=\frac{5}{.49}=10.2 \text{ sec.} \tag{43}$$

The coordinates of the point (b″) are therefore:

(V + dv) = 25.4 m. p. h. and (t + dt) = 26.5 sec.

The corresponding point on the distance curve is found as follows

$$ds=\frac{20.4+25.4}{2}\times 1.467\times 10.2=342 \text{ ft.} \tag{46}$$

s = 244 + 342 = 586 ft. from start.

Neglecting the grade which is encountered at a distance of 14 ft. beyond the above point and continuing the above "step by step" method the values listed in Table VII may be determined and the acceleration portion of the diagram plotted to the point (i′) where the speed becomes constant.

TABLE VII.

CALCULATED DATA, SPEED, AND DISTANCE TIME CURVES.

dv	V+dv	dt	t+dt	ds	s+ds
5	25.4	10.2	26.5	342	586
3	28.4	10.7	37.2	421	1007
3	31.4	22.2	59.4	974	1981
3	34.4	49.1	108.5	2370	4351

Assuming the total braking resistance including train resistance b = 150 lb. per ton which, of course, will produce a deceleration of 1.5 m. p. h. p. s., a straight line may be drawn back from T = 159 sec. with the above deceleration as its slope. Such a line is Tr′, Fig. 21.

The train resistance during coasting should be selected as nearly as possible to the value which, on the train resistance curves (Fig. 17), corresponds to the average speed expected during the coasting period. The value of 15 lb. per ton is often taken arbitrarily to represent this resistance and will therefore be used in this problem. Since this corresponds to a deceleration of 0.15 m. p. h. p. s., a line with this slope is drawn in the position (f′k), cutting the braking line at point k′.

If the area of the diagram (Ob′b″f′k′T) be measured with the planimeter it will be found to contain approximately 123 section squares. With the particular scales of speed and time used each square is equivalent to a distance of 36.6 ft. The diagram therefore represents a distance of 123 x 36.6 ft. = 4500 ft. which is greater than the length of the run. The coasting line must therefore be redrawn parallel with itself but starting with a lower initial speed until, by the "cut and try" method, until the area of the diagram is found to correspond to the length of the

run in feet. Such a diagram is that bounded by the lines (Ob′b″l′m′T), Fig. 21. If the true coasting resistance be now determined it will be found to be 13.5. The assumption of 15 was therefore conservative.

The distance time curve will be of value in approximating the correct area of the diagram. The values of distance from Table VII plotted against time would produce the curve of distance covered by the car if it were to be allowed to reach constant speed. However, since the power is shut off and coasting begun at a speed of 27.5 m. p. h., a new distance curve must be determined beyond this point.

The distance corresponding to point (l′) is found as follows:

$$\text{Avg. } V = \frac{27.5+25.4}{2} = 26.5 \text{ m. p. h.}$$

$$t = 33 \text{ sec.}$$

$$ds = 26.5 \times 1.467 \times (33-26.5) = 252 \text{ ft.} \qquad (46)$$

$$s = 586+252 = 838 \text{ ft. from start.}$$

Continuing the calculations of distance corresponding to the coasting and braking portions of the diagram the distance time curve (On′n″p′) is determined which at 159 seconds checks very closely the length of the run.

Speed and Distance Curves for Actual Grades.—If the actual grades listed in Table VI be considered, the curves take quite a different and more complex form. Since it was found in the previous calculations that the point (b″) corresponded to a distance but 14 ft. short of (B), Table VI, where the grade changes to 6 per cent. it will introduce little error and simplify the calculations considerably to consider the grade beginning at this point.

Since the 6 per cent. grade will cause an immediate reduction in speed, a decrement of 3 m. p. h. will be assumed.

$$dv = 3 \text{ m. p. h.} \quad V = 22.4 \text{ m. p. h.} \quad \text{Avg. } V = 23.9 \text{ m. p. h.}$$

$$(f'') \text{ at } 23.9 \text{ m. p. h.} = 15.4 \text{ lb. per ton.}$$

$$\text{T.E. at } 22.4 \text{ m. p. h.} = 600 \text{ lb.}$$

$$p'' = \frac{600}{6.25} - 15.4 - 120 = -39.4 \text{ lb.} \qquad (41)$$

$$\text{Deceleration} = 0.394 \text{ m. p. h. p. s.} \qquad (42)$$

$$dt = \frac{3}{.394} = 7.6 \text{ sec.}$$

New point on curve has coordinates as follows:

$$V = 22.4 \text{ m. p. h.} \quad t = 26.5 + 7.6 = 34.1 \text{ sec.}$$

$$ds = 23.9 \times 1.467 \times 7.6 = 266 \text{ ft.} \qquad (46)$$

$$s = 586 + 266 = 852 \text{ ft.}$$

The corresponding point on the new distance time curve is therefore determined.

Following this method, being careful to observe every change of grade at its correct distance from the start, the rather irregular curve (Ob′b″s″l″m″T) results. If the distance corresponding to each of the steps assumed for the speed time curve be calculated the distance time curve (On′n″p″) may be plotted. If it be remembered that the slope of the distance time curve $\frac{ds}{dt}$ represents speed, the effect of grades in reducing speed will readily be detected if the two distance curves are compared.

While the amounts of coasting in both of the speed time curves considered are very generous, the effects of grades both in reducing the possible coasting and in increasing the coasting deceleration in the second case are marked. If stops were necessary in this distance the coasting periods would be greatly shortened and possibly eliminated if the same schedule speed were maintained.

Current and Power Curves.—The gross tractive effort during the constant acceleration period (Oa′), Fig. 21, was found to be 850 lb. which required a current value per motor of 84 amperes. During the first half of this same period plotted to the same scale on Fig. 23 therefore, the current per pair of motors in a four motor equipment is 84 amperes while the current per car is 168 amperes. In the second or parallel half of the period, however, the corresponding values of current are 168 and 336 amperes respectively. In determining the other points on the current curve such as the current after 20 seconds have elapsed, for example, it is found from Fig. 21 that the speed is 22.5 m. p. h. Referring to the speed characteristic, Fig. 13, the corresponding current is found to be 64 amperes per motor or 256 amperes per car since all four motors

are now operating in parallel. This value is plotted against a time abscissa of 20 sec. on Fig. 23. Following out this method the current required for operating the car over the level track will be represented by curve (OO″fkb″lq′), Fig. 23, while the corresponding current with the actual grades introduced is illustrated in curve (OO″fkb″mnq″).

As an average voltage of 500 volts has been assumed on this road the ordinates of the two similar curves of Fig. 24 are 500 times those of Fig. 23 reduced to the convenient scale of kilowatts. If these curves be compared with the speed time curve, Fig. 21, the increased values of power required as the car enters the grades will be noted.

The areas of the two kilowatt time diagrams, Fig. 24, are 3960 and 12,100 kilowatt seconds respectively. Applying formula (48) the energy required by the level run is,

$$E=\frac{3960}{3600}=1.1 \text{ kw. hr.} \tag{48}$$

while that of a run involving the existing grades is,

$$E=\frac{12100}{3600}=3.36 \text{ kw. hr.} \tag{48}$$

The energy consumptions for the two runs expressed in watt hours per ton mile are,

$$E_1=\frac{3960 \times 1000 \times 5280}{3600 \times 25 \times 4200}=55.3 \text{ w. hr./ton mile.} \tag{49}$$

$$E'_1=\frac{12100 \times 1000 \times 5280}{3600 \times 25 \times 4200}=169 \text{ w. hr./ton mile.} \tag{49}$$

Since the rolling stock and equipment in this case are rather lighter than that of average interurban practice the value of 55.3 watt hours per ton mile for the level track is rather a low figure while the steep grades in the latter case render the figure 169 for E'_1 rather above the average. The very fact, however, that these values of energy vary over so wide a range illustrates the marked effects which may be attributed to local conditions and emphasizes the necessity of a complete and detailed study of each proposed road before accurate estimates can be made of its cost of construction or dependable conclusions drawn regarding the advisability of its installation.

CHAPTER X.

SPEED TIME CURVES (STRAIGHT LINE).

The method of plotting speed time curves outlined in the previous chapter is most desirable for final calculations where considerable accuracy is necessary. For preliminary approximate results, however, it is not necessary to go to this refinement and the so-called "straight line" speed time curve described below is therefore used.

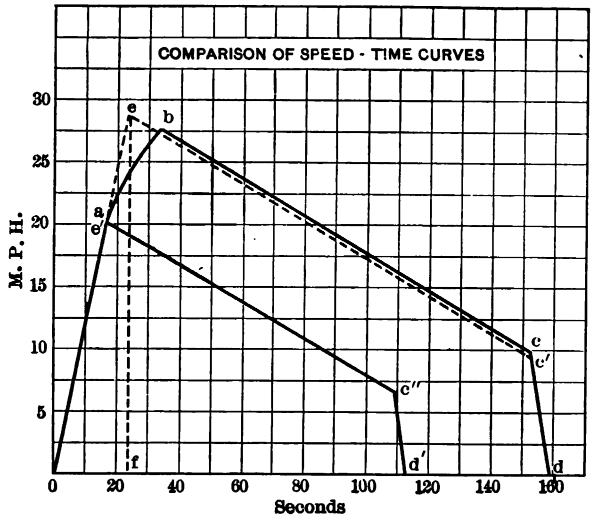


FIG. 26.

In Fig. 26 will be found reproduced the speed time curve (Oabcd) calculated in Chapter IX for a straight level track, Fig. 21. If, now, the time (Od) and the distance, represented by the area (Oabcd), are kept constant and the acceleration be assumed constant, *i.e.*, the acceleration portion of the figure a straight line, the diagram (Oaec′d) may be drawn with the same area and with the average assumed coasting and braking decelerations of 0.15 m. p. h. p. s. and 1.5 m. p. h. p. s. respectively. Such

a chart, although it may vary considerably in some details from the more accurately drawn curve previously considered, is extensively used for rapid calculations of possible schedules for a given road and for the rough determinations of required equipment and preliminary estimates.

Granted that the straight line diagram is sufficiently accurate for most practical purposes, an unlimited number of similar speed time diagrams may be plotted for the same distance and time by varying the rate of acceleration but with constant coasting and braking decelerations. Such a series of diagrams for a 1 mile run in 120 sec. appears in Fig. 27,[1] in which (OBC) represents

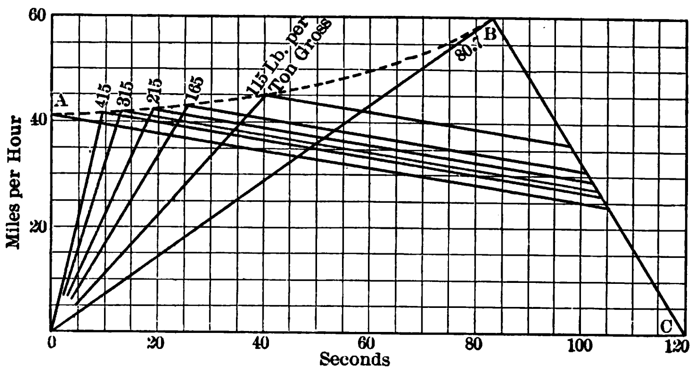


FIG. 27.—Typical Speed Time Curves. (Varying rates of Acceleration.)

a run with no coasting and therefore the lowest possible rate of acceleration, while the other extreme case, which is of course theoretical only, is represented with an acceleration (OA) infinitely great. Between these two limiting values there are a number of possible selections to be made, the gross tractive efforts listed on the chart including the net effort necessary for acceleration plus the 15 lb. per ton train resistance assumed for all diagrams. It should be noted that the dotted line (AB) is the locus of maximum speeds for all diagrams.

Furthermore, if the distance still remain constant at 1 mile and the time for the entire run be varied the more complete chart, Fig. 28,[1] results, which is made up of a series of charts like Fig. 27,

[1] Taken from "Electric Traction," by A. H. Armstrong.

each having its own acceleration variations for a fixed distance and time. The dotted curve of Fig. 28 represents the locus of maximum speeds necessary to cover the distance of 1 mile in any given time represented as an abscissa. For example, if it be desired to cover the mile run in 150 sec., the braking line terminating at 150 sec., shows the maximum speed with any acceleration to be 48 m. p. h. corresponding to a gross tractive effort of 51.2 lb. per ton. If other rates of acceleration are possible the particular chart designated by the point 51.2 may be treated as outlined in Fig. 27.

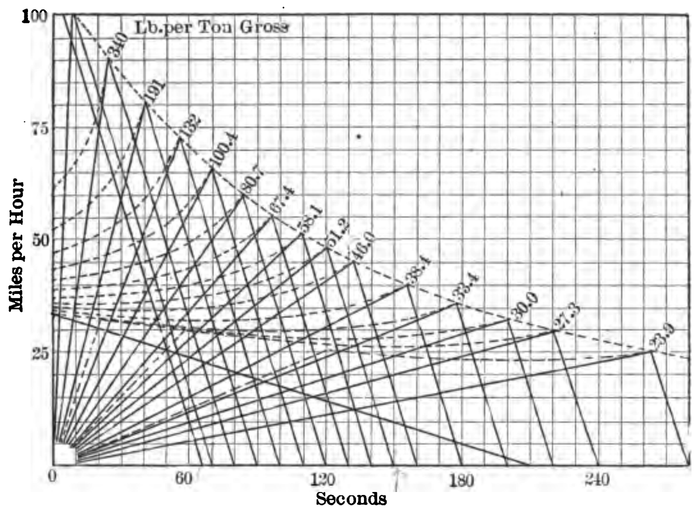


FIG. 28.—General Speed Time Curves.

These charts are of little use, however, unless readily applicable to various lengths of run. Such application may be made in the following manner.

It can be readily proved geometrically that the ratio of the altitudes or bases of two similar trapezoids is that of the square root of their areas. The speed-time diagrams which have been considered in this chapter are trapezoids with altitudes representing maximum speeds, bases representing time, and therefore with areas expressed in terms of distance. If the length of run be changed, keeping the same acceleration and coasting and braking

decelerations, the diagrams for the two lengths of run will remain similar and the following formulæ may be derived for the calculation of maximum speed and time.

T = Schedule time for original run.

T' = Schedule time for new run.

S = Distance of original run.

S' = Distance of new run.

V_m = Maximum speed of original run.

V'_m = Maximum speed of new run.

$$\frac{T'}{T}=\sqrt{\frac{S'}{S}} \tag{50}$$

$$\frac{V'_m}{V_m}=\sqrt{\frac{S'}{S}} \tag{51}$$

As an illustration of the use of these formulæ, it will be assumed that the speed-time diagram is desired for a run one-half the length of that considered in the previous chapter (2100 ft.), Fig. 26, with the same rate of acceleration, coasting, and braking. From the diagram the following values may be scaled:

$T = (Od) = 159$ sec.

$V_m = (ef) = 28.5$ m. p. h.

$S = 4200$ ft.

Substituting in equations (50) and (51)

$$T' = 159\sqrt{0.5} = 112.4 \text{ sec.} \tag{50}$$

$$V'_m = 28.5\sqrt{0.5} = 20.1 \text{ m. p. h.} \tag{51}$$

Plotting these values, the diagram (Oe′c″d′) results and therefore represents fairly accurately a speed-time curve for a distance of 2100 ft. with a minimum of labor involved in its determination.

Energy Calculations.—As the acceleration was assumed constant in the above diagrams, it is usually not sufficiently accurate to derive from them the current and kilowatt-time curves as was done in Chapters VIII and IX. The energy required for the run may be closely approximated, however, by the following method, which may also be used to advantage as a check on the power-time curves when the latter are plotted by the "step by step" method.

Assume the following nomenclature.

V = Average speed in m. p. h.

V_c = Initial coasting speed in m. p. h.

V_b = Initial braking speed in m. p. h.

r = Total train resistance in lb. per ton including $(f \pm g + c)$.

E_1 = Energy in watt hours per ton mile.

m = Mass of car $= \frac{2000W}{g}$.

b = Braking force at periphery of car wheel in lb. per ton.

S_c = Distance travelled from beginning of coasting period to stop with no braking.

S_b = Distance travelled from beginning of braking period to stop.

t_c = Time of coasting in sec.

t_b = Time of braking in sec.

$$E_1 = \frac{V \times 5280 \times r \times 746}{60 \times 33000\ V} = 1.99\ r \tag{52}$$

This may be considered with little error to be $(2\ r)$.

This represents in simple form the net power at the wheels of the car. To obtain the gross input to motors this must be divided by the efficiency of the motors with gears included.

Energy During the Braking Period.—Furthermore, it should be noted that neither equation (52) nor the formulæ of Chapter VIII include the power required to stop the car. To determine this power exerted during the braking period, proceed as follows:

$$e = \frac{m(V_b \times 1.467)^2}{2} \tag{53}$$

but

$$e = S_b\ (b + r) \tag{54}$$

therefore

$$WS_b\ (b + r) = \frac{2000\ W\ (1.467\ V_b)^2}{2\ g} \tag{55}$$

The power during the braking period is therefore

$$\text{H. p.} = \frac{\text{Ft. lb. per min.}}{33000} = \frac{60\ WS_b\ (b + r)}{33000\ t_b}$$

or simplified

$$\text{H. p.} = \frac{60 \times 2000\ W\,(1.467\ V_b)^2}{32.2 \times 2 \times 33000\ t_b} = 0.121 \frac{WV^2_b}{t_b} \tag{56}$$

Coasting Energy and Train Resistance.—If, however, the above reasoning be applied to the results of a coasting test in which the car or train is allowed to coast to a standstill from various initial speeds the train resistance may be calculated thus

$$WS_c r = \frac{2000\ W\ (1.467\ V_c)^2}{2\ g} \tag{57}$$

whence

$$r = 66.8 \frac{V^2_c}{S_c} \tag{58}$$

By thus combining the straight line speed-time charts with the calculation of energy from the above formulæ, a rapid although approximate method of calculating train performance is provided which will be found of great convenience.

PART II.

POWER GENERATION AND DISTRIBUTION.

CHAPTER I.

SUBSTATION AND POWER STATION LOAD CURVES.

Whereas the previous chapters have been devoted to the operation of cars and trains with the ultimate object of determining the demands which they may make upon the power distribution system, it is now necessary to study the combination of individual train demands and their connection with the average and maximum loads on the substation and power station.

The load curves of substation and power station have been treated simultaneously for the reason that the substation of a large urban railroad or a relatively long interurban line acts as a source of power for the surrounding distribution system and therefore, as far as the determination of station output and capacity are concerned, it matters little whether the machines supplying the cars are in turn furnished with electrical power over a high tension transmission line or whether they are driven by engines or turbines.

The most convenient units in which quickly to express the power demands of a train were found to be "watt hours per ton mile." This demand was shown to vary greatly with schedule speed, weight of cars, condition and profile of track, length of run, etc. It is clear, therefore, that except in very exceptional cases, a single value of energy cannot be applied for the entire length of an interurban run from terminal to terminal. Occasionally, however, with a straight level right of way, with fairly constant schedule speed throughout the run and with all cars of about the same size and weight, an average value of energy may be used for all cars for the entire run and the average substation demand for the day determined as follows:

E = Energy in kilowatt hours.
E_1 = Energy of car in watt hours per ton mile.
W = Weight of car in tons.
S_s = Length of section supplied by station in miles.

N = Number of trips in both directions over section per day determined from graphical train schedule.

Eff. = Efficiency of distribution system in per cent.

The energy demand upon the substation in a day is therefore

$$E = \frac{NWE_1S_s}{1000 \times \text{Eff.}} \qquad (59)$$

The average load on the station in kilowatts during the day is

$$L = \frac{E}{\text{Hours operation per day}} \qquad (60)$$

If it were not for the excessive current taken during the acceleration period as compared with the full speed running current, the maximum load on the station might be determined by multiplying the average power required per car (average ordinate of the kilowatt-time diagram, Fig. 24) by the maximum number of cars operating upon a single substation section at any one time. This method will usually give too low a maximum demand, however, and it is therefore necessary to find the maximum number of cars starting simultaneously on a single section. For such cars the maximum ordinate of the power time curve, Fig. 24, must be used together with the average ordinate of the curves of such other cars as may be running upon the section at the same time. To correctly determine the number of cars starting at any one time a great deal of judgment and knowledge of local conditions is necessary in addition to a familiarity with the train schedule. If there be a siding located on the section it is safe to assume at least two cars starting simultaneously.

While this method of determining average and maximum loads upon a substation has been successfully used in practice, especially where preliminary estimates only were involved and the runs between stations on a given section were quite similar in all respects, the more detailed method outlined below is usually finally adopted.

A series of speed, current, and kilowatt-time curves are plotted for the entire road, one curve for each run between stations. If more than one class of service, such as local, limited, freight, etc., is proposed, a similar series of curves must be plotted for each.

From the kilowatt-time curves it is possible to scale off the area representing the energy taken by the car or train during any particular interval of time throughout the run. The combined areas of all these curves may readily be expressed in terms of kilowatt hours per run or, better, the portion of the run which is shown by the time abscissa and train schedule to be on a given substation section may be thus treated. It is only necessary, therefore, to integrate all types of runs throughout the day on a given section in order to obtain the total energy and average load on the station in a similar manner to that of equations (59) and (60).

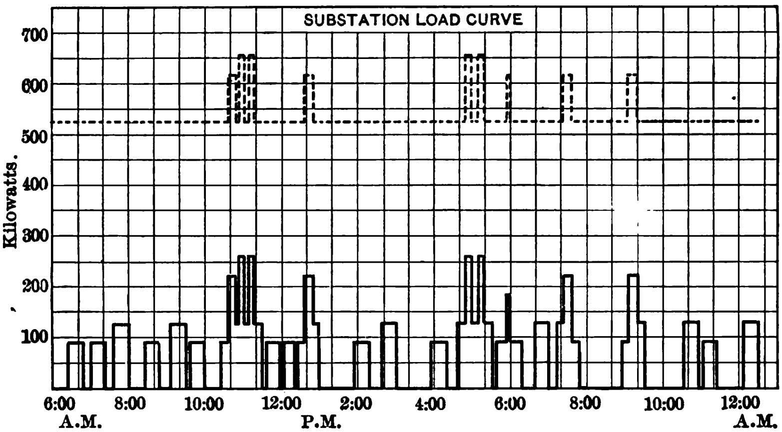


FIG. 29.

The problem may be carried one step farther if necessary and the ordinates of kilowatt-time diagrams of all trains on the section for each increment of time added together to form the most accurate load diagram which it is possible to predetermine for the substation.

Many modifications of these two methods will present themselves to the engineer as best fitted to local conditions and to the degree of accuracy required. Fig. 29, for example, is a load diagram made up of rectangular areas, each representing the average kilowatt-hour demand of all cars on one of the 12 mile substation sections of an existing interurban road at a given hour of the day. The average load on the station found by taking the average ordinate of this curve for the day is 69.3 kw.,

while the maximum demand from the upper curve plotted with reference to the possible number of cars starting simultaneously on the section is 655 kw.

In plotting station load curves by whatever method, it must be remembered that most roads have not only the daily fluctuations of load which will be shown by the peaks of the load time curve plotted for a single day, but there is usually considerable difference between the load curves for the various seasons of year, even the train schedule being changed for one of less headway in the summer season. This fact, together with the possibility of sudden daily demands due to special attractions along the line of the interurban road, especially upon holidays, must be given careful attention in applying load curves to the location and design of substations and power stations.

Load Factor.—The "load factor" of a station for a given period has been defined as the ratio

$$\frac{\text{Average power demand}}{\text{Maximum power demand}} \qquad (61)$$

although it is often considered as the ratio of average demand to station capacity. The load factor, as determined from the load curve of the substation in this particular case is therefore,

$$\frac{69.3}{655} = 10.6\% \qquad (61)$$

While a low load factor is to be avoided if possible, since it follows that such a factor involves the use of relatively large station equipment operating at light and therefore low efficiency loads; yet in interurban practice where the traffic is relatively light and the trains few in number but demanding large amounts of power, as compared with the city systems, it is hardly possible to improve conditions of load factor to any great extent over the particular case which has been used as an illustration.

CHAPTER II.

Distribution System.

The circuit which the propulsion current for a car follows extends from the feeder panel of the substation over the out-going feeders and trolley to the car motors, thence through the rails back to the substation switchboard or, in some cases, directly to the negative terminal of the converter. The voltage at the substation is maintained constant, usually at 550 or 600 volts. The current flowing over the above circuit causes a drop of potential in proportion to the resistance of the entire circuit in accordance with Ohm's law. This fall of potential subtracted from the substation potential determines the voltage at the car. As the latter voltage should be as high and as constant as possible if good service is to be maintained, it follows that the resistance of the feeders and track return should be carefully proportioned. The latter will be discussed in detail under the subject of "Bonds and Bonding," Chapter VI, while this chapter will be devoted to the study of the overhead trolley and feeder system.

On interurban roads and often in the city systems the trolley is sectionalized by the introduction of circuit breakers in the trolley wire which insulate one section from another. Cables from either side of the breaker are carried to a pole switch by means of which the sections may be connected together if necessary. Each section is generally supplied with power from a single substation through the agency of feeders paralleling the trolley for a portion of its length. The trolley wire itself for mechanical reasons is usually from No. 00 to No. 0000 B & S gauge hard drawn copper and is often installed double with wires about 6 in. apart but electrically connected at every hanger. Where the current required is considerable this practice is very commendable, for the second trolley replaces an equal amount of copper which would otherwise be installed in the insulated feeder and, what is of greater consequence, it eliminates

all overload switches and frogs in the trolley wire at sidings, the wires being spread as the tracks are separated, the car trolley always remaining on the right wire. With the size of trolley given, together with a well bonded track of known weight and resistance, the problem resolves itself into one of feeder design.

Since the problem is necessarily treated differently for interurban and urban roads the former will be first considered. The minimum permissible voltage at the car under the worst conditions must first be assumed. While this voltage drops at times in interurban practice to 250 volts, a value of at least 350 volts

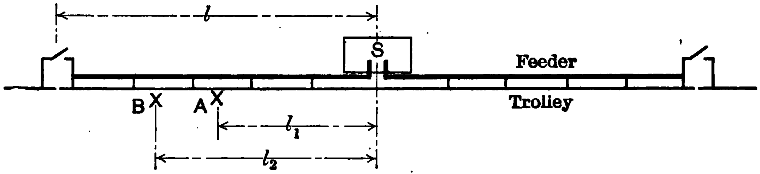


FIG. 30.—Continuous Feeder Distribution.

should be used. This allows 250 volts drop in the distribution system under maximum traffic conditions. Reference to the train schedule will determine this maximum condition which usually involves two cars starting simultaneously and possibly others operating on the same section. Assuming the simplest form of distribution, Fig. 30, with the feeder paralleling the trolley for the entire length of the section and tapping into it sufficiently often so that they may be considered as one wire of large section, the following solution may be outlined.

e = Permissible voltage drop.
l = One-half length of section in feet.
l_1 = Distance of car (A) in feet.
l_2 = Distance of two cars at (B) in feet.
I_A = Current taken by one car at (A).
I_B = Current taken by two cars at (B).
R_T = Resistance per ft. of track (two rails).
R_{FT} = Combined resistance per ft. of feeder and trolley.
r = Resistance of copper per mil. ft.

As in mechanics the combined loads I_A and I_B, determined from the current-time curve, may be considered as acting through

the equivalent distance (l_g) of the center of gravity of load from the substation where

$$l_g = \frac{I_A l_1 + I_B l_2}{I_A + I_B} \tag{62}$$

Volts drop in track $(e_{TT}) = l_g R_T (I_A + I_B)$ (63)

Allowable drop in feeder and trolley

$$e_{FT} = e - l_g R_T (I_A + I_B) \tag{64}$$

$$R_{FT} = \frac{e - l_g R_T (I_A + I_B)}{(I_A + I_B) l_g} \tag{65}$$

Combined area of feeder and trolley in

$$\text{circular mils} = \frac{r l_g}{R_{FT}} \tag{66}$$

Having determined the necessary combined area of feeder and trolley from equation (66), or from the wire tables, the known area of the trolley wire or wires may be subtracted and the necessary size of feeder remains.

Assuming for illustration two cars whose current-time curves are represented in Fig. 23 starting 3 miles from the substation and a similar car running at full speed 2 miles from station. The trolley consists of two No. 4/0 B & S wires and the track is of 70 lb. rail with 9 in. bonds equivalent to one-half the rails in conductivity. The resistance of copper may be taken as 10.6 ohms per mil. ft.

Armstrong gives the resistance of third rails and track rails with the above bonding in the following table.

TABLE VIII.

RESISTANCE OF THIRD RAIL AND TRACK.

Wt. of rail per yd.	40	50	60	70	80	90	100	110
Third rail resistance, ohms per mile.	.093	.074	.062	.053	.046	.042	.038	.034
Two track rails resistance, ohms per mile.	.066	.053	.044	.038	.033	.033	.027	.024

I_A from Fig. 23 = 672 amp.

$I_B = 160$ amp.

$$L_G = \frac{5280(672 \times 3 + 160 \times 2)}{832} = 14{,}800 \text{ ft.} = 2.8 \text{ mi.} \qquad (62)$$

Volts drop in track $= 832 \times .038 \times 2.8 = 88.5$ volts (63)

Allowable drop in feeder and trolley = 161.5 volts (64)

$$R_{FT} = \frac{161.5}{832 \times 14800} = .0000131 \text{ or } .0131 \text{ ohms per 1000 ft.}$$

Corresponding area from wire table = 800,000 c.m.

Two 4/0 trolley wires = 423,200 c.m.

Feeder section = 376,800 c.m.

Either a standard 350,000 or 400,000 c.m. cable might be chosen.

If, in place of isolated sections of trolley, the wires be continuous from terminal to terminal and the substations connected in

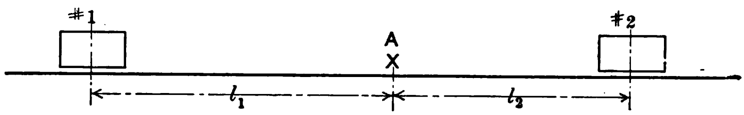


FIG. 31.—Division of Current between Substations.

parallel with one another between trolley and rail, such a problem as that assumed above would involve the determination of the portion of the current per car which was supplied from each of the two adjacent stations. Here again the principles of mechanics may be applied as illustrated in Fig. 31 where (A) is a car at distances (l_1) and (l_2) from substations No. 1 and No. 2 respectively. If the car is drawing a current (I_A) it may be safely assumed that its current demand on substation No. 1 is

$$I_1 = \frac{l_2 I_A}{l_1} \qquad (67)$$

while the current taken from No. 2 is

$$I_2 = \frac{l_1 I_A}{l_2} \qquad (68)$$

With this understanding a problem in feeder calculation similar to the above offers no additional difficulties.

Each half of the section in Fig. 30 was considered independently of the other for the reason that the feeders and trolleys of

the two halves of the section are in parallel and therefore the voltage drop in one does not affect the other. The solution of a problem with the substation located at the end of the section would therefore be treated in a similar manner.

In many cases, however, feeders are tapped into the trolley at infrequent points, thus forming a network whose calculation is slightly more involved. Such a condition is illustrated in Fig. 32. The feeder is tapped to the trolley at the two points (a) and (b) at distances from the station of (l) and (l_1) respectively. Two cars are starting at (B) at a distance (l_2) from the station with total current (I_B).

Volts drop in track $= I_B R_T l_2$ (69)

Allowable drop in feeder and trolley $e_{FT} = e - I_B R_T l_2$ (70)

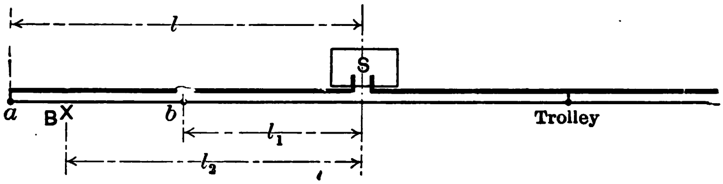


FIG. 32.—Feeders with Infrequent Taps.

In any branched circuit problem such as this it is always most convenient to make use of Kirchoff's laws which may be stated as follows:

First, "At any point in a circuit, the sum of the currents directed toward the point is equal to the sum of those directed away from it."

Second, "In any closed circuit the algebraic sum of the (IR) drops is equal to that of the (e. m. f. s.)."

While in this simple problem it is obvious without stating such a law that the current entering the cars at (B) is the sum of the two currents arriving at (B) by the two paths from (a) and (b) respectively and also that the drop in potential between (B) and (b) must be the same by either path, yet in complicated networks, especially in city streets, the statement of Kirchoff's laws in this form is most acceptable.

The resistance from (b) to (B) direct is that of $(l_2 - l_1)$ ft. of trolley or

$$R_{bB} = R_W(l_2 - l_1) \tag{71}$$

if (R_w) represents the resistance of the trolley per foot. The corresponding resistance by path (a) is

$$R_{aB} = R_w(l - l_2) + R_F(l - l_1) \tag{72}$$

with (R_F) representing resistance of feeder per foot. The currents in the two branches may now be calculated from the two equations

$$I_B = I_a + I_b \tag{73}$$

$$\frac{I_a}{I_b} = \frac{R_{bB}}{R_{aB}} \tag{74}$$

With the current in each branch known, the fall of potential between point (b) and the car (B) may be determined from either of the equations

$$e_{aB} = I_a(R_{aB} + R_{ba}) \tag{75}$$

$$e_{bB} = I_b R_{bB} \tag{76}$$

That these two drops in voltage are identical will be shown more conclusively by substituting in (75) the value of current (I_a) obtained from equation (74).

As the total current (I_b) is flowing through the feeder between (b) and (S) the additional drop over this distance is

$$e_{bs} = I_b R_F l_1$$

The total drop in the overhead conductors between substation and car is therefore,

$$e_1 = I_b R_{bB} + I_b R_F l_1 \tag{77}$$

If the feeder had been tapped into the trolley at the substation (S) in addition to the other taps a second network would have been added to the calculation, but the method of solution would not have been changed. In fact, any network may be readily solved with the use of Kirchoff's laws if taken step by step.

City Systems.—The principal difference between the calculation of urban and interurban feeder systems is that in the former it is necessary to consider a large number of cars per section, each drawing an average current which may be readily determined from their relative current-time curves or from actual tests with meters on the car if the road is already in operation. Such sections may ordinarily be considered as uniformly loaded without serious error.

Such a section, represented by Fig. 33, may be treated as a uniformly loaded beam in mechanics and in place of using the individual values of current taken by each car at a, b, c, etc., the total current of all cars on the section combined may be considered as being taken from the mid-point, distant l/2 ft. from the station. The correctness of this method may be readily proved by integrating the voltage drops (ir dl) between the limits of zero and the length of the line (l) where (i) represents the current per foot and (r) the resistance per foot respectively.

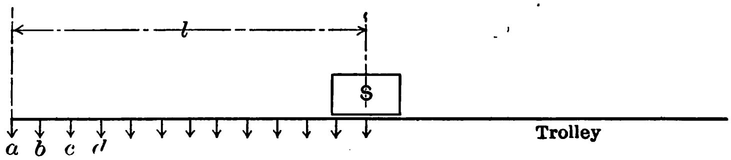


FIG. 33.—Uniformally Loaded Distribution Section.

Having now but the single equivalent current to consider, the problem may be solved as in the case of interurban systems previously described.

Although the limiting voltage drop is always the first consideration in railway feeders, it is well to check the safe carrying capacity of the cable selected by the above methods with the actual current which is flowing therein, the safe carrying capacities for open wiring being readily found in any electrical handbook.

Financial Considerations.—While the foregoing calculations will give the proper size of feeder to be installed for a given minimum potential at the car, it may be found that because of too great an assumed distance between stations or for other reasons the cost of the copper is prohibitive. Some consideration must therefore be given to the amount of power lost in the distribution system, and the relation of its annual cost to the interest and depreciation on the copper to be installed.

If the I^2R losses be summed up for each portion of the distribution section or if this same total loss be obtained from the product of the squared current by the equivalent resistance of the overhead conductors and rail return, the efficiency of the

distribution system and the annual cost of power lost in distribution may be determined from the following equations.

$$\text{Effy. Dist. System} = \frac{\text{Power delivered to car}}{\text{Power delivered to car} + I^2R \text{ loss}} \quad (78)$$

$$\begin{array}{l}\text{Annual cost} \\ \text{of distribu-} \\ \text{tion loss}\end{array} = \left(\frac{I^2R \text{ loss}}{1000} \text{ x hours per year}\right) \text{ x } \left\{\begin{array}{l}\text{Cost of power} \\ \text{in cents per} \\ \text{kw. hr. at d. c.} \\ \text{buses of sub-} \\ \text{station.}\end{array}\right. \quad (79)$$

Kelvin's law states that the most economical size of feeder to install is that in which the annual cost of power loss is equal to the interest and depreciation figured on first cost of installation. As the annual cost of power loss for a given length of feeder and current transmitted will decrease, while the interest and depreciation charges will increase as the size of the cable increases, curves of these costs plotted with size of cable as abscissæ will intersect at the most economical size of wire to be installed. Such curves plotted for a current of 100 amperes in 1000 ft. of feeder with interest taken at 6 per cent. and depreciation at 2 per cent. will be found from Fig. 34 to determine a feeder size of 375,000 c.m. section for which either the 350,000 or 400,000 c.m. standard size might be selected. The calculations from which these curves were plotted involved a cost of power of one cent per kilowatt hour and a cost of copper installed of 20 cents per pound.

Since any one of these feeder calculations taken by itself may give results which are unfavorable when all requirements of the distribution system are considered, it is the duty of the engineer to calculate the proper feeder sizes necessary for a satisfactory line drop, to check these calculations for carrying capacity and by Kelvin's law and then to determine the relative weight to be given to the considerations of fall of potential, carrying capacity, and relative cost of power loss in the particular system in question.

High Voltage Direct Current Distribution.—While it will be seen in the following chapter that the substation connections are somewhat different in the case of the comparatively few roads operating with a direct current voltage of 1200 volts on the trolley,

the distribution system is materially the same as for 600 volts, the potential being applied between trolley and rail as before with the necessary feeders paralleling the trolley for a portion of the length of the line and tapping into same at points where the voltage would otherwise be too low.

The principal difference between the two systems is the greater distance between substations and therefore the fewer substations

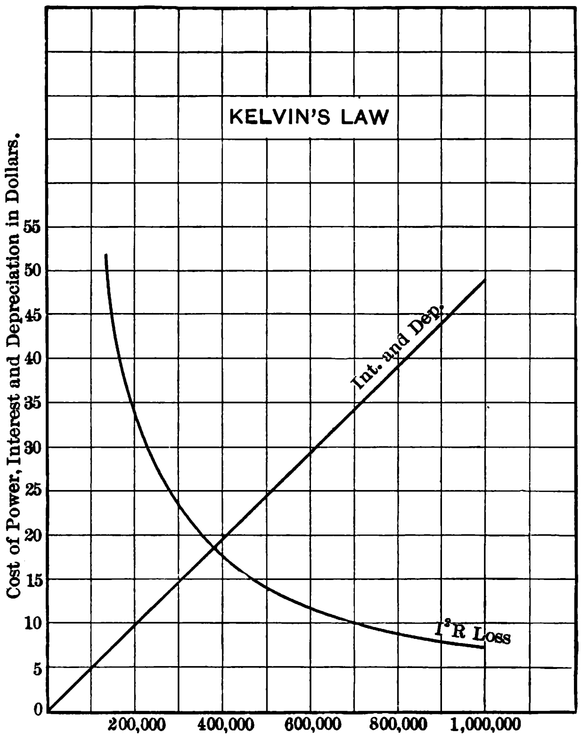


FIG. 34.

required. As the distance to which power may be transmitted with the same percentage loss and first cost of copper varies directly with the distance, it is clear that with 1200 volt supply the substations may be double the distance apart; and, although the distribution feeders may be longer, they have to transmit but one-half the current for a given load, and are therefore but one-half the area necessary for 600 volt service. The method of cal-

culation of feeder sizes is, however, identical with that explained above.

Single-phase Distribution.—With the introduction of railway equipment designed for operation from a single-phase trolley, the distribution system is changed slightly. While the trolley and track return are still used, the voltages applied to the trolley have been increased to 3300, 6600, or 11,000 volts and in

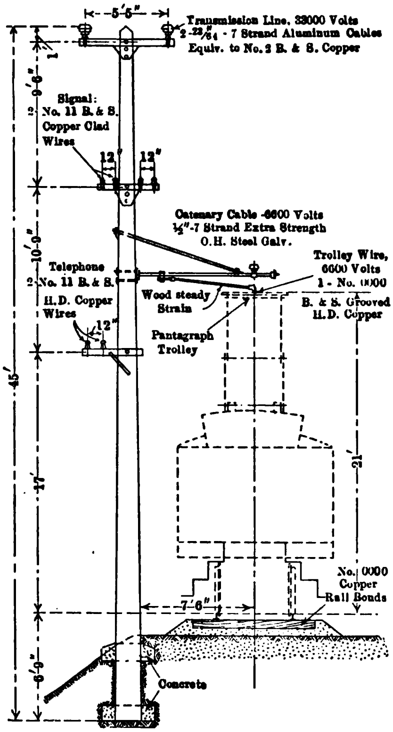


FIG. 35.

order to render high speed current collection reliable with the further advantage of longer spans and better insulation the so-called "catenary" construction has been generally adopted. This design involves the use of one or two steel messenger wires freely suspended in spans of several hundred feet each, with a convenient amount of sag, which in turn support the trolley wire by means of vertical hangers of varying length spaced about ten feet apart and

so adjusted that the trolley wire hangs perfectly level. This eliminates the usual vertical rise of the trolley pole at supports with the accompanying tendency to leave the wire at such points when operating at high speed. Such single catenary construction on the Chicago, Lake Shore, and South Bend Railway is well illustrated by the typical elevation, Fig. 35, while the more complicated but stronger construction used by the N. Y. N. H. & H. R. R. in its New York terminal electrification will be found in Fig. 36.

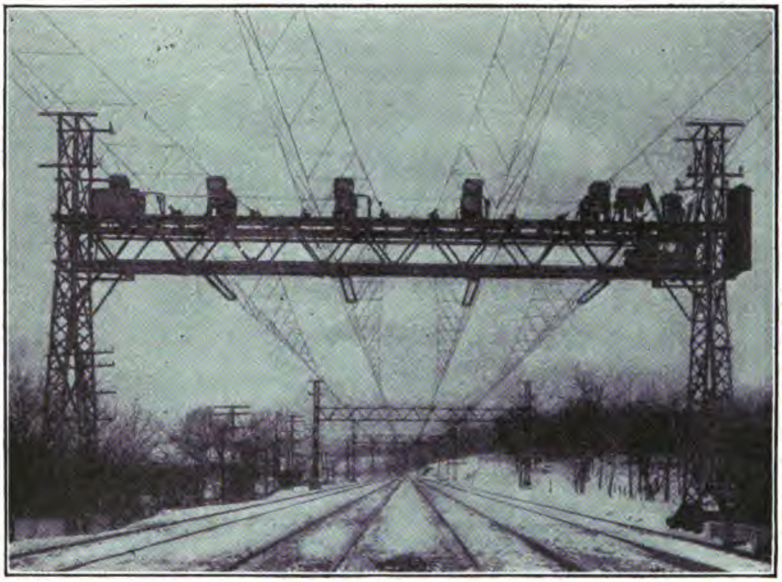


FIG. 36.

With the higher trolley voltages used with this system, the substations, if necessary at all, are much farther apart and trolley sections usually longer. Upon the shorter roads the transmission line and substation may often be eliminated, while the possible generation of power at 6600 or 11,000 volts often permits the step-up and step-down transformers to be omitted as well with a corresponding decrease in first cost of installation and maintenance. Three-phase generation is generally adopted because of the lower cost and small size of three-phase generators as compared with single-phase units. This necessitates balancing

the load as closely as possible on the three phases which is best accomplished by entirely insulating adjacent trolley sections from one another and feeding three consecutive sections from each of the three phases. Such construction, of course, will not permit tying trolley sections together in case of emergency as in direct current distribution.

In some instances three-phase generators are operated as single-phase machines at about two-thirds their rating. The simplicity of single-phase distribution and the ability to tie

FIG. 37.

adjacent sections of trolley together lend some advantages to this system for the shorter roads.

The calculation of single-phase distribution systems is based upon the same laws as those previously outlined in detail, it being necessary only to substitute impedance for resistance in determining fall of potential in trolley feeder and track. It will be remembered that the apparent resistance or impedance of a conductor to the flow of alternating current is slightly greater than for direct current depending upon the size and material of the conductor as well as its position with respect to the return circuit. Tables of impedances for different sizes and spacings of wires

will be found in all electrical handbooks. The power loss calculations for a given current are identical with those of the direct current system as the impedance does not enter these equations.

Third Rail Distribution.—Practical difficulties in collecting large currents at high speeds by means of an overhead trolley have led to the installation of an insulated third rail or contact rail at the side and slightly above the running rails to which the positive feeders are connected and from which the current is collected by one or more iron contact shoes carried by each car. These shoes ordinarily bear on the head of the rail with their own weight but in some instances the third rail is inverted and protected with an insulating shield, in which case the shoe is pressed upward against the head of the rail by means of springs. Typical protected third rail construction is illustrated in Fig. 37, which shows very clearly the necessary break in the third rail at street crossings. This break is electrically bridged by means of a copper cable installed in conduit under the crossing.

The calculations for third rail installations are identical with those for direct current trolley distribution, the resistances of the third rail, Table VIII, replacing those of the trolley wires.

The relative advantages and disadvantages of the various systems whose method of distribution has been briefly described above will be compared in Part IV, Chapter I.

CHAPTER III.

Substation Location and Design.

There is probably no question which the engineer of a proposed electric railway system has to decide that is more dependent upon good engineering judgment and common sense than that of the location of substations and power stations. Many theoretical rules and formulæ have been devised for the purpose of calculating the most economical location of such a station and many of these must be given consideration and granted their proper weight in the final decision, but they are of little value when taken alone and often lead to serious errors when given too much prominence or when adopted with too little reference to local engineering and financial relations.

With this foreword a few of the most important of these theories will be discussed, their relative importance being decided in each case by local and particularly by financial conditions. If the distinction between the design of alternating current substations for single-phase lines and substations supplying 600 volt direct current as subsequently outlined are kept in mind the following considerations may readily be applied to either type of station.

Substation Location.—When a substation is being considered whose function it is to supply power to a network of lines in a limited district of a large city system, one of the important considerations, as in the case of the power station, is to locate the station as nearly as possible at the center of gravity of the load. This center of gravity may be conveniently determined graphically as in problems in mechanics as follows. Locate the principal centers of distribution in the district, such as prominent street crossings and points from which several feeders radiate and determine the average load at these points as well as their distance apart. These may be graphically represented as in Fig. 38 with the loads considered as weights at the corners

of the diagram which is drawn to a convenient scale of distance. The center of gravity of the loads (A) and (B) would obviously be at (E) where $\frac{AE}{BE}=\frac{500}{200}$ and AB or $(AE+BE)=1.5$ mi. while (D) and (C) might be combined into a single load of 1650 kw. at (F) where

$$\frac{DF}{CF}=\frac{1000}{650}$$

The center of gravity of (E) and (F) with loads of 700 and 1650 respectively located at (G) will therefore be the center of gravity of the system and from the standpoint alone of supplying the loads most economically this should be the location of the station.

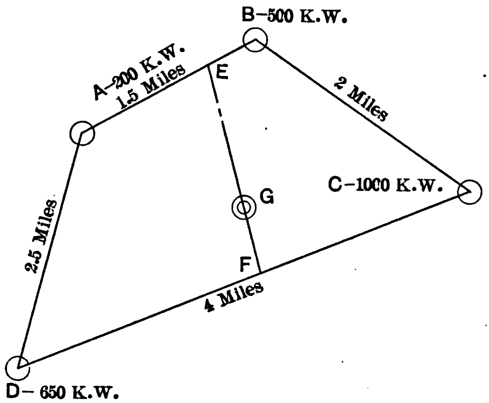


FIG. 38.—Center of gravity of power demands.

With the more common problem, however, of locating substations for interurban lines where the loads are usually located in a single straight line, the question to be decided is how far apart should the stations be placed in the single direction and therefore how many and what capacity stations are necessary. The maximum distance between stations is limited by the voltage of the distribution system and in the case of the more common 600 volt direct current distribution the distance between stations seldom exceeds 12 miles, each station feeding 6 miles in either direction. Whether this distance shall be diminished or slightly increased in each particular case depends largely upon the following considerations.

As the number of substations for a given road is increased and therefore the distance between them diminished the governing factors will vary as outlined below.

The total cost of buildings and real estate will usually increase in direct proportion to the increase in the number of stations. This statement is, of course, subject to the qualification that such spacing of stations does not locate one or more of them in the centers of towns or cities, or in such other places as may increase their cost from the standpoint of high land values or expensive architectural effects.

The cost of attendance will increase directly with the number of stations as the increased capacity of the fewer stations would seldom if ever require more attendants than the small station unless the station were located in a congested city district where the high cost of real estate necessitated double decking the station.

The substation equipment will cost more with the increased number of stations but not proportionately more. Whereas much of the equipment will have to be duplicated with each station that is added and although the cost of small units is greater per kilowatt capacity than that of large machines, yet if all the stations considered are of fairly large capacity the relay capacity necessary for overloads of long duration and for emergency use will not be as great with an increased number of stations. This may be illustrated by assuming a total average demand upon all substations of 2000 kw. If two substations are decided upon, it would be good practice to install three 500 kw. units in each, or a total of 3000 kw., thus leaving one 500 kw. machine in each station as a relay. If, however, four stations seem advisable of 500 kw. average demand each, it is probable that three 250 kw. units would be used in each station requiring the same total of 3000 kw. While the switchboards, wiring, lightning protection, etc., would therefore cost double the amount for the four stations, the machines and transformers would be increased in cost only by the increase per kilowatt of small as compared with large units, which increase between units of 250 and 500 kw. is not great. Where the total demand on all stations is much less than that assumed in this case, however, the small station is at a disadvantage with respect to relay capacity and the in-

creased cost of equipment may equal if not exceed the rate of increase in number of stations.

The losses in substation machinery will increase slightly with increase in the number of stations because of the lower efficiency of smaller units and the increased no-load losses of the larger number of machines running light or idle for a portion of the time as is often the case in interurban stations.

The cost of distribution copper and the losses in the distribution system will decrease with the increase in the number of stations, as the length and therefore the cost and resistance of feeders will decrease as the stations are moved nearer together.

In order to reduce all of these quantities to common terms for comparison, an annual charge representing a certain perdetermined percentage of the first costs involved must be combined with the annual cost of attendance, maintenance, and power losses. This percentage of the first cost which becomes an annual charge in all estimates of this nature is termed a "fixed charge" and involves interest on investment, taxes if any, insurance and depreciation on the equipment. This charge may be accurately estimated in each instance but is often assumed a total of 11 per cent. of the first cost whenever local conditions are such as not to eliminate any of the above mentioned items involved in its makeup. If, therefore, a curve be plotted between ordinates representing the sum of fixed charges, annual cost of power losses, and maintenance and abscissæ expressed in terms of number of substations, the total annual cost curve will result and because of the fact that some of the factors are increasing and some decreasing with an increase in the number of stations, a minimum point on the curve will be found which will denote the proper number of substations to install and therefore the distance between stations, considered solely from the standpoint of the factors involved in the curve.

Such a method as that outlined above appears rather involved, requiring as it does at least a tentative station location, design of equipment, and feeder loss calculation for each group of stations considered. Since the capacity alone and not the detailed plan of the station changes with increased number of stations, and as the feeder losses in an interurban system will vary approximately

in proportion to the length of the feeders, the number of calculations necessary for such a curve is not great and, as the cost variations when thus graphically plotted are easily studied and compared, the solution is well worthy of serious consideration. Chapter II on the "Distribution System" will aid materially in the construction of these curves.

It will be noted that nothing was said regarding the variation of transmission line costs and losses in the above discussion. While these factors may occasionally enter the problem in the case of city stations with underground high tension lines, yet in the case of interurban installations the transmission line usually parallels the road for nearly the entire distance, often looping through each of the substations en route. With such construction, it will be seen, the transmission line first cost and annual losses will not vary appreciably with substation location, especially for the reason that in the case of long lines with relatively small power requirements the transmission line wire is much larger than that required for any electrical considerations because of the mechanical strength needed. Even in high tension underground systems the substations are usually tied together by such a network of primary feeders for the sake of reliability of service that the first cost and annual losses in the primary system may be considered practically independent of the number of stations providing the total output does not change.

Another important factor which should not be overlooked, especially when express and freight service is contemplated, is the question of combining the substation, waiting station, and freight or express depot into one building with a material saving in the item of substation attendance, since the substation operator can often attend to the other duties of the passenger station as well.

If the station be not operated throughout the twenty-four hours the question of living accommodations for station attendants must be given some attention as the theoretical determination might locate the substations in localities where no attendants would be willing to live even though the railway company provided living apartments in the substation building as is often the case. With some of the shorter systems it is possible to connect the various sections of trolley and feeders through the substation switchboard

to the 600 volt direct current supply of the power station and thereby enable the first car in the morning to run over the line before the substations are started. With such an arrangement the operators may live in the nearest town to the substation.

Substation Design.—Assuming the most common type of substation whose function it is to transform energy supplied by a high tension alternating current transmission line into direct current at approximately 600 volts, the principal factors entering into its design will be briefly discussed.

With a knowledge of the load demand curve and the efficiency of the distribution system and with the number and location of substations determined, the average and maximum loads on the substation may be found as outlined in Chapter I. To decide upon the proper capacity of units to be installed, however, is largely a matter of good judgment. Since it is now standard practice to rate electrical machinery for a possible 25 per cent. overload for two hours without overheating, the duration of the peak load must be studied as well as its magnitude. It must also be known whether or not there is a possibility of greater loads at any time during the year and also what the growth in power demand is likely to be within the next few years. With these facts in mind it is well to provide for the average power by the installation of two or more units, usually leaving one unit as a relay in case of emergency. This relay unit should ordinarily be as large as the other units in the station in order that it may take the place of another machine in case of break down. Units of less than 200 kw. are seldom installed and if the average load is less than this value, the 200 kw. machines are usually run at light load rather than install smaller units. This procedure involves relatively large idle relay capacity as well but the smallest units are usually less reliable and offer little reserve capacity or inertia in case of sudden overloads.

In the problem taken for illustration in Chapter I the average demand is 69.3 kw., while the maximum demand is 655 kw. The low average value is due to the fact that during several rather long periods there is no car on the section and the unit is therefore running light. Further study of the curve will show that a load of 130 kw. is maintained for an hour at a time while peaks

of 260 kw. exist for fifteen minutes. A 200 kw. machine would supply the average load and these latter peak loads but would not be of sufficient capacity for the peaks of 655 kw. caused by the simultaneous starting of two cars. A 300 kw. unit would therefore be necessary for this station as it could withstand the momentary overload of 100 per cent. This case is a good example of the necessity of taking the overloads and their duration into account in such determinations.

Synchronous Converter vs. Motor Generator.—Having determined upon the proper capacity for the unit a decision should be made between the synchronous converter and the motor generator. The former machine consists of a synchronous alternating current motor and direct current generator combined into a single unit with but one frame, armature, and field. It is really a direct current generator with the armature winding tapped to slip rings at symmetrical points, which rings are supplied with alternating current as in the case of the synchronous motor. The motor generator, as its name implies, is an alternating current motor direct connected to a direct current generator. The motor may be either of the synchronous or induction type.

The advantages of each type of unit for railway substation service are briefly set forth in the following paragraphs:

Advantages of Motor Generator.—The ratio between a. c. and d. c. voltage is not fixed. For transmission voltages not exceeding 13,000 this set may therefore be operated without step-down transformers if the motor be wound for transmission line voltage.

The d. c. voltage may be readily controlled by means of the generator field rheostat without affecting the a. c. voltage or power factor.

The d. c. generator may be automatically compounded or over-compounded without auxiliary apparatus. The converter requires an external reactance in addition to the series field.

The motor generator is not as sensitive to commutation troubles, especially upon sudden overloads, as the converter.

"Hunting," or the periodic variation in speed on either side of an average value, with the usual accompaniments of poor commutation and "arcing over" are less marked in the syn-

chronous motor generator set because of its greater inertia, while they are entirely absent in the induction motor set.

The power factor of the synchronous motor generator set is controlled quite as easily as with the converter. The induction motor set, of course, has the disadvantage of low uncontrollable power factor.

Advantages of Synchronous Converter.—This machine has a higher efficiency.

Its rating for a given size of frame is much higher.

The floor area taken up is considerably less.

Its cost is less for a given capacity although, in cases where the adoption of the motor generator enables the transformers to be eliminated, the first cost of the converter with transformers is about the same as that of the motor generator alone.

Methods of Starting.—Upon comparison of methods of starting there is found to be no choice between the two types of machines since both may be started from either the d. c. or a. c. side and with the latter method both machines may be started by either the variable voltage method of the General Electric Company or the auxiliary induction motor method of the Westinghouse Company. If the direct current method of starting is adopted a starting rheostat must be provided which in turn will be controlled by a multi-point switch usually mounted on the switchboard. This switch starts the converter from the 600 volt feeder system as an ordinary d. c. motor, gradually cutting out resistance until the motor comes up to speed, when the man d. c. switch may be closed. The speed may then be varied by changing the field excitation until the a. c. side is synchronized, by means of the synchroscope or synchronizing lamps, as in the case of the synchronous motor or alternator.

With the variable voltage method of starting low voltage taps are taken from the bank of transformers to a double throw switch usually located on a separate panel near the converter. When the switch is thrown down a low voltage, usually about one-third rated voltage, is impressed on the armature of the converter and the machine starts as an induction motor. As the converter approaches full speed the armature is supplied with full voltage by throwing the starting switch into the "up" position.

This method requires a rather large starting current at low power factor but has the advantage of eliminating the necessity of synchronizing. In both the above methods it is necessary to open the shunt field winding of the converter in several places in order that the excessive voltage otherwise induced in the many turns of the field by the large circulating currents in the armature may not puncture the field winding.

If the auxiliary induction motor method be used a small induction motor, sufficiently large to start the converter with no load and bring it to slightly above synchronous speed, is mounted on the end of the converter shaft. This motor is usually operated by means of a three pole starting switch on the switchboard which is supplied with power from auxiliary transformer connections. As the converter reaches its proper speed it is synchronized with the transmission line as in the first case. The starting motor is then cut out of circuit.

As each type of unit has many advantages and as both are in general use in railway substations it will be left to the engineer of each particular system to weigh the advantages and disadvantages with reference to the local conditions under which they are to operate and to make the decision. It may be safely stated that the converter was at first installed almost universally in railway substations, but during the last few years the motor generator set has proved a formidable competitor and has been installed in many instances largely because of the commutation and hunting troubles which have been connected with the operation of the converter in practice.

Transformers.—If synchronous converters are installed to maintain a constant direct current potential, the secondary alternating current voltage which must be supplied to them is at once determined, since with the single armature of the converter there is a definite ratio between a. c. and d. c. voltages. This usually requires the installation of step-down transformers in order to lower the transmission line voltage to that value required by the converters. Even if motor generators are installed the transmission line voltage for interurban roads is usually so high that transformers are necessary in the substation.

In Fig. 39 will be found an efficiency curve for a 750 kw.

three-phase synchronous converter from which it will be noted that although the efficiency falls off with light loads as with all other electrical machines, it may be considered constant for all loads above 50 per cent of its rating. The rated capacity of the converter divided by this efficiency constant will give the necessary transformer output. In this country almost universal preference has been shown for single-phase transformers combined into banks, usually of three each, in place of three-phase

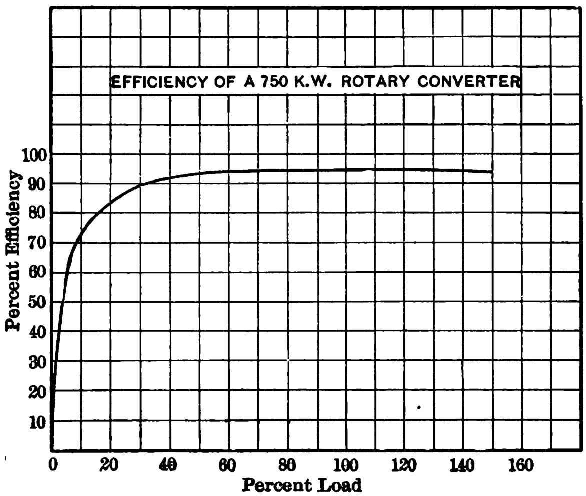


FIG. 39.

transformers. This is largely because of the increased flexibility of the system with smaller units and the avoidance of crippling the transformers of all phases in case of damage to a single unit. The rating of each transformer will therefore be determined as follows in the more common three-phase installation.

$$\text{Transformer kw.} = \frac{\text{Converter kw.}}{3 \times \text{converter effy.}} \qquad (80)$$

A bank of three transformers, each of the above rating, should be installed for each converter or motor generator usually with switches in both high and low tension connections. The transformer connections may be either the well known "delta" or "star" on both primary and secondary, or either set of windings may be connected "delta" with the other "star" remembering

that with fixed transmission line and converter voltages the rated voltage of the transformers will be less than line voltage in the ratio of $\frac{1}{\sqrt{3}}$ if the "star" connection be adopted. The "delta" connection has the advantage of continuing three-phase operation with two transformers "V" connected in case of damage to one unit without change of connections. Its further advantage of changing to "star" connection at some future time in case it seems desirable to raise the transmission line voltage should not be neglected in making a decision.

Table IX will be found convenient in selecting transformer voltages for converters of various types. This table is based upon 600 volts at the direct current side of the machine and while it represents average practice it must be remembered that the voltage ratio is dependent upon the design of machine and may therefore vary slightly with machines of different manufacture.

TABLE IX.
VOLTAGE RATIOS IN SYNCHRONOUS CONVERTERS.

	Actual ratio.			Theoretical ratio.
	Zero load.	Full load (straight).	Full load (inverted).	
Single phase.......	429	435	423	424
Three phase......	366	372	360	367

In many substations six-phase synchronous converters will be found operating upon three-phase transmission systems. This procedure is adopted because of the higher efficiency and greater output of the six-phase machine for the same size of frame. The connections and switching apparatus of the six-phase converter are necessarily more complicated than with the three-phase machine. From Table X which illustrates the increased capacity of converters of different phases for the same size of frame it will be noted that a six-phase converter has nearly double the capacity

of the same machine operated as a direct current generator and nearly one and one-half times that of a three-phase converter. If a sufficently large commutator and brush rigging be provided

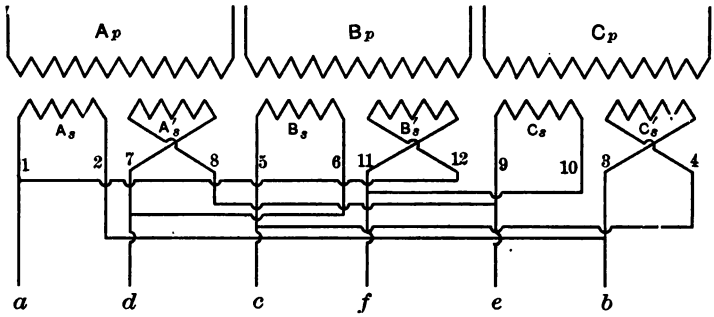


FIG. 40.—Six-phase "delta" connections from three-phase primaries. (Double secondary required.)

on a three-phase machine rated at 500 amperes, it may be used as a six-phase machine, if properly connected, for an output of 725 amperes with the same temperature rise.

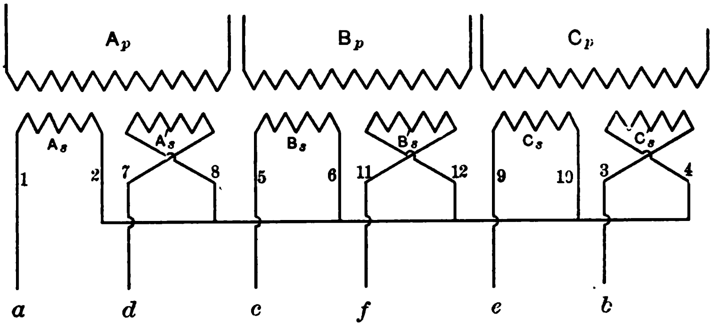


FIG. 41.—Six-phase "star" connections from three-phase primaries. (Double secondary required.)

TABLE X.[1]

COMPARATIVE RATINGS OF CONVERTERS.

D. c. generator.	Single-phase converter.	Three-phase converter.	Two-phase converter.	Six-phase converter.
1.00	0.85	1.32	1.62	1.92

[1] Elements of Electrical Engineering, Vol. II, Franklin and Esty.

The above discussion has a direct bearing upon the question of transformer connections, for if a six-phase converter be installed one of the methods of connection illustrated in Figs. 40, 41, and 42 must be adopted if the three-phase supply is to be retained.

Transformers may be further classified with regard to their method of cooling as follows:

1. Oil cooled.
2. Air cooled.
3. Water cooled.

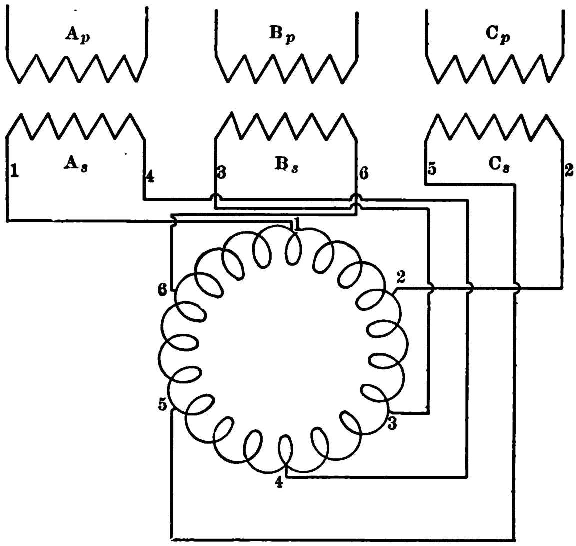


FIG. 42.—Six-phase diametrical connections from three-phase primaries. (Single secondary only.)

Transformers of the "oil cooled" class depend for their cooling upon the natural circulation of a comparatively large body of oil within the transformer case, all the heat being radiated from the surface of the corrugated iron cases. This construction is suitable for transformers of all potentials and for capacities up to 500 kw.

Air cooled transformers are cooled by means of an air blast provided by a motor driven blower and forced through the air ducts of the transformer core. This method of cooling requires

the construction of air ducts in the floor, usually of concrete, and involves the additional cost of blower outfits. It is suitable for all capacities but is limited to potentials of 33,000 volts or less.

Transformers of the third class contain a series of pipe coils within the case, the insulating oil circulating around the coils while the latter are cooled by means of circulating water within. This type of transformer is used for all the largest installations and is not limited as to capacity or voltage.

Compounding Reactances.—One of the disadvantages of the synchronous converter is the difficulty of compounding the machine for constant or increasing d. c. voltage with increase of load. This difficulty arises from the fact that when the field strength of the converter is varied its direct current voltage is not appreciably changed. The converter acts as a synchronous motor in this respect, the increase of field strength causing the motor to draw a leading current from the line. It is this latter feature that makes it possible to compound the converter if an external reactance be connected in series with each of the phases between the transformers and the converter. If the machine be designed to give rated voltage at a light load with the reactance in circuit, it follows that the leading current produced by a series field as the load increases will neutralize the inductive voltage of the reactance coil and thereby impress an equal or even higher voltage on the converter at full load. As there is a fixed ratio between the a. c. and d. c. voltages, the latter is compounded at the same time. The combination of series field and external reactance is therefore necessary for compounding a converter, whereas the former only is required for the d. c. generator of the motor generator set.

Switchboard.—The typical substation switchboard consists of the following classes of panels:

1. High tension line.
2. High tension transformer.
3. A. c. converter or motor generator.
4. D. c. converter or motor generator.
5. Totalizing.
6. D. c. feeder.

The number of panels in each class is dependent upon the size of

station and the number of converters it contains but all panels of each class are usually grouped by themselves.

The two classes of high tension panels are usually of the remote control type. This is universally the case above 13,000 volts. With this construction the high tension switches are mounted in fire-proof compartments of concrete, tile, or brick and may therefore be located at some distance from the control board. No high tension lines are connected with the control board, the switches being operated by means of auxiliary 125 volt d. c. circuits and the meters connected with the secondary windings of current and potential transformers whose primary windings are in the high tension circuits. Red and green illuminated bulls-eyes on the switchboard panels indicate whether the main switches are closed or open respectively.

The high tension line switches control the connections between high tension lines and the station bus bars, while each bank of transformers is connected to the high tension buses by means of the switches controlled by the panels of the second group. These latter switches and often both groups of switches are provided with inverse time limit relays which act as circuit breakers in case of overload, with the further provision that they may be adjusted to operate only after the overload has continued for a prearranged interval. The "inverse" type of relay is in addition so designed that the greater the overload, the shorter will be the time in which it will open. With the transformer relays set for a very short interval, the high tension line switches arranged so as to open a fraction of a second later if the overload still continues and with the relays in the out-going high tension feeders at the power house adjusted for an interval of one or two seconds, it will be seen that only those switches connecting apparatus or lines upon which there is trouble will be opened and the interference with other service reduced to a minimum.

The meters to be installed on the first two groups of panels often vary widely with the personal preference of the engineer in charge, an average equipment probably consisting of an ammeter in each phase, a power factor meter and a voltmeter on a swinging bracket at the end of the board.

The panels of group three contain all equipment necessary for

the control of the a. c. side of the converter or motor generator as the case may be and usually include a low voltage secondary a. c. switch for connecting converter to transformers, motor field rheostat in case of a synchronous motor generator set, starting switch if starting motor be used, together with synchronizing and voltmeter plugs. The instruments usually consist of three ammeters and a power factor meter.

The direct current panels perform the office of connecting the direct current or output side of the converter or motor generator to

FIG. 43.

the direct current bus bars. For this function three single pole switches are usually employed, one positive, one negative, and an equalizer switch. The negative and equalizer switches are often located on a pedestal or on the frame of the converter thereby simplifying the switchboard connections. The field rheostat control of the converter or of the generator of the motor generator set is located on this panel together with a circuit breaker, a d. c. potential receptacle, and a starting switch in case it is planned to start the machine from the d. c. side. The meters are usually confined to a main ammeter and indicating wattmeter with a d. c. voltmeter on a swinging bracket. In large installations a field ammeter is often included on this panel.

The totalizing panel contains instruments only and these are so connected as to measure the total output of the station between the d. c. converter panels and the outgoing feeders. An ammeter or indicating wattmeter and an integrating wattmeter are usually installed. This panel is often entirely omitted and the latter instrument mounted on the sub-base of one of the other panels.

The out-going feeder panels may be designed to control one or two feeders each. Single pole (positive) switches and circuit breakers in series with ammeters make up the usual equipment for each feeder.

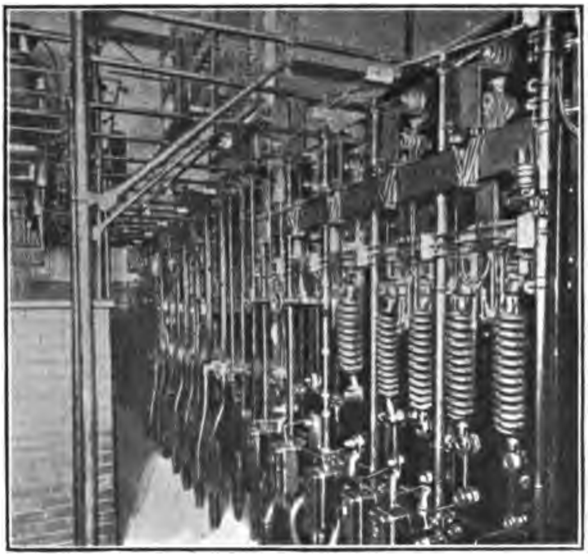


FIG. 44.

The entire board is usually of the standard size 90 in. in height including a 28-in. sub-base with panels varying in width from 16 to 36 in. Blue Vermont marble forms the principal material of construction although low voltage boards are often built of slate. The board should be spaced at least 4 ft. from the wall and the wiring at the back should be generously lighted. Where gallery boards of the remote control type are installed from which the operator may view all the machines

under his control, the "desk type" of board has been quite frequently specified. In Figs. 43 and 44 will be found views of typical railway substation switchboards.

Storage Battery Auxiliary.—While the storage battery is looked upon by many engineers and managers as an evil to be avoided, it certainly has its important place in the substation equipment of many roads. Its possible function is three-fold, although it is often installed for the purpose of meeting but one of the following requirements:

1. To aid in maintaining constant potential.
2. To supply all peak loads above a certain predetermined average.
3. To assume the entire load of the substation for a short period of time.

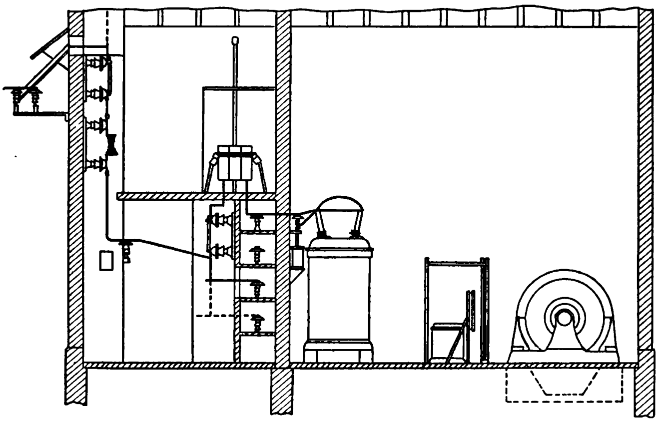


Fig. 45.

When the second and third functions listed above are assumed by the battery, its capacity must be rapidly increased, yet in many instances batteries of sufficient capacity to fill these three requisites are maintained in practically all substations of the road.

As the maintenance and depreciation of a battery is relatively high, the local problem must be carefully studied before a decision can be reached. Such a study should balance the fixed charges of the battery and accompanying control equipment combined with

its maintenance, against the fixed charges of the relay equipment and the extra line copper that would otherwise have to be installed, plus the rather intangible factors of irregular schedule due to variable voltage and total interruption to service.

Arrangement of Apparatus.—There is little variation in the arrangement of apparatus in a railway substation except in the extreme cases where it is necessary to locate the equipment on

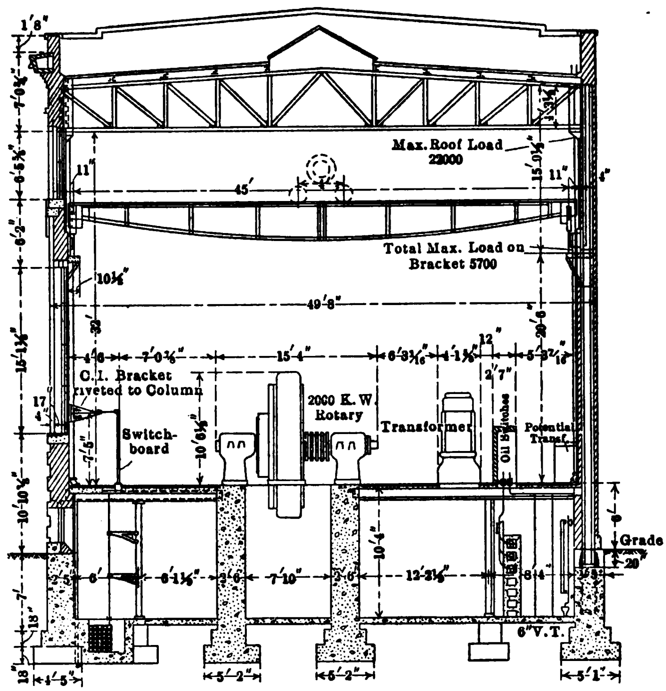


FIG. 46.

two floors. The high tension apparatus is usually confined to a separate room and is often located in fire-proof vaults. The converters, reactances, and switchboard are usually located very close together in a single room with the wiring either in conduit embedded in the floor or of the open type supported from insulator racks on the basement ceiling. The principal features which tend materially to alter the design of a substation are the overhead or underground entrances of high tension and d. c. feeder cables.

Typical stations involving each type of construction are illustrated in Figs. 45 and 46.

Wiring.—The wiring of the station is usually figured from the standpoint of carrying capacity only, as the potential drop for the short distances involved is generally negligible. The resistances of the d. c. cables between converter and switchboard should, however, be carefully balanced in order to divide the load properly between two or more machines operating in parallel.

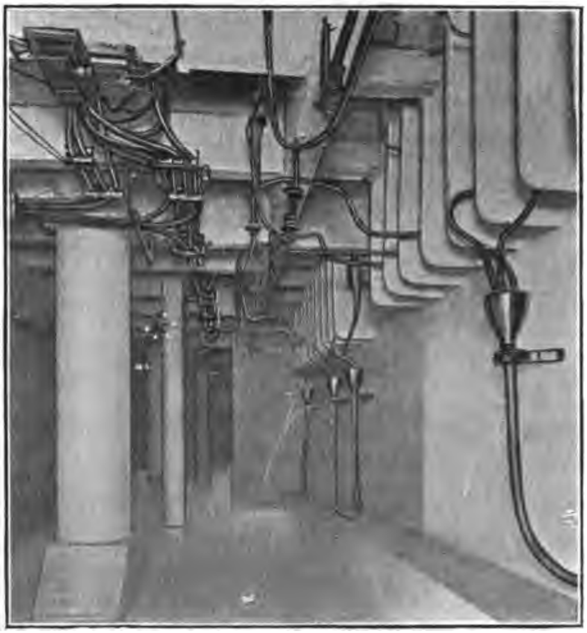


FIG. 47.

The low tension wiring and the high tension cables up to 13,000 volts are usually insulated with rubber, paper, or varnished cambric and protected either with braid or a lead sheath. Such construction is well illustrated in Fig. 47, while a simplified wiring diagram for a typical substation will be found in Fig. 48. Wiring above 13,000 volts, and often that at lower voltage is carried on line type insulators with no further insulation, these lines often being run in individual concrete or brick compartments with con-

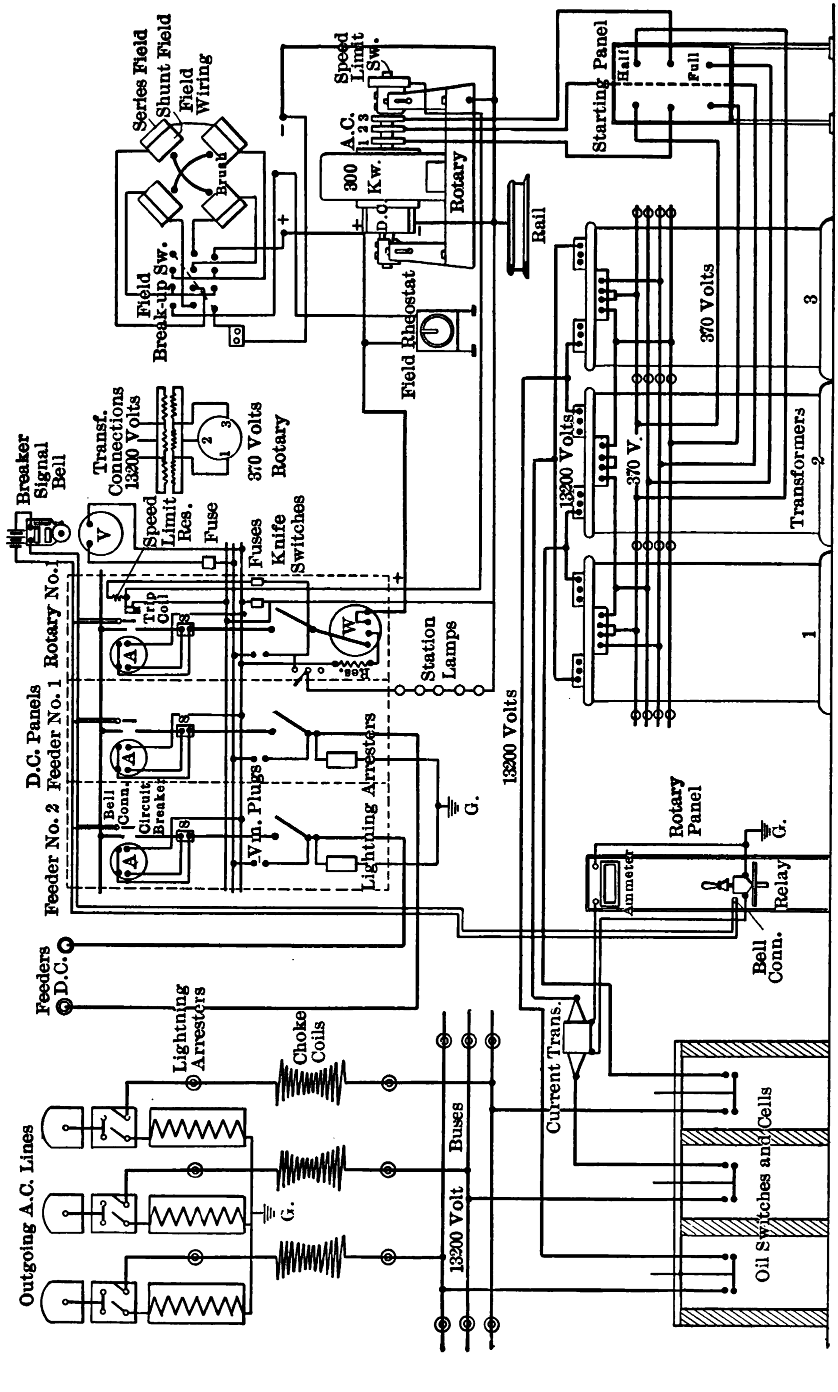

Outgoing A.C. Lines
Lightning Arresters
Choke Coils
G.
13200 Volt
Buses
Feeders
D.C.
Feeder No. 2
Feeder No. 1
Rotary No.
D.C. Panels
Bell Conn.
Circuit Breaker
Vm. Plugs
Lightning Arresters
G.
Station Lamps
Breaker Signal Bell
V
Speed Limit Res.
Fuse
Fuses
Knife Switches
Trip Coil
W
Transf. Connections 13200 Volts
370 Volts Rotary
Field Break-up Sw.
Series Field
Shunt Field
Field Wiring
Brush
Field Rheostat
Rail
300 Kw.
A.C. 1 2 3
D.C.
Rotary
Speed Limit Sw.
Starting Panel
Half
Full
370 Volts
370 V.
13200 Volts
Transformers
1
2
3
13200 Volts
Rotary Panel
Ammeter
Relay
G.
Bell Conn.
Current Trans.
Oil Switches and Cells

FIG. 48.

venient chambers provided for sectionalizing or disconnecting switches and instrument transformers.

Lightning Protection.—The incoming high tension lines and the outgoing railway feeders are each provided, just within the wall of the station, with a helix of wire of the same size as the line wire which acts as a "choke coil" to divert high frequency surges to the lightning arresters connected between the coils and the

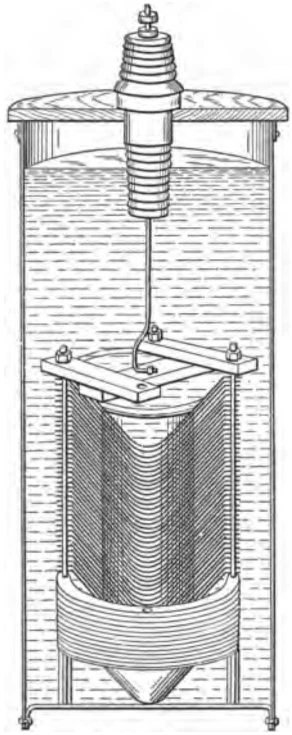


FIG. 49.

outside lines. These arresters which will be found described at length in manufacturers' bulletins usually comprise a series of spark gaps between the lines and ground which will permit a discharge to pass when an excessive voltage occurs and yet quench the arc which would otherwise follow over the gaps when supplied with normal line potential. The recent type of electrolytic arrester, Fig. 49, however, interposes a series of liquid films of high resistance in place of the spark gaps and is therefore self

healing. Two objectionable features of this arrester, however, are its tendency to freeze in cold weather and the necessity of "charging" it from time to time to maintain the films of electrolyte in working order.

Portable Substations.—On many roads traffic demands become excessive upon certain days or weeks of the year on differ-

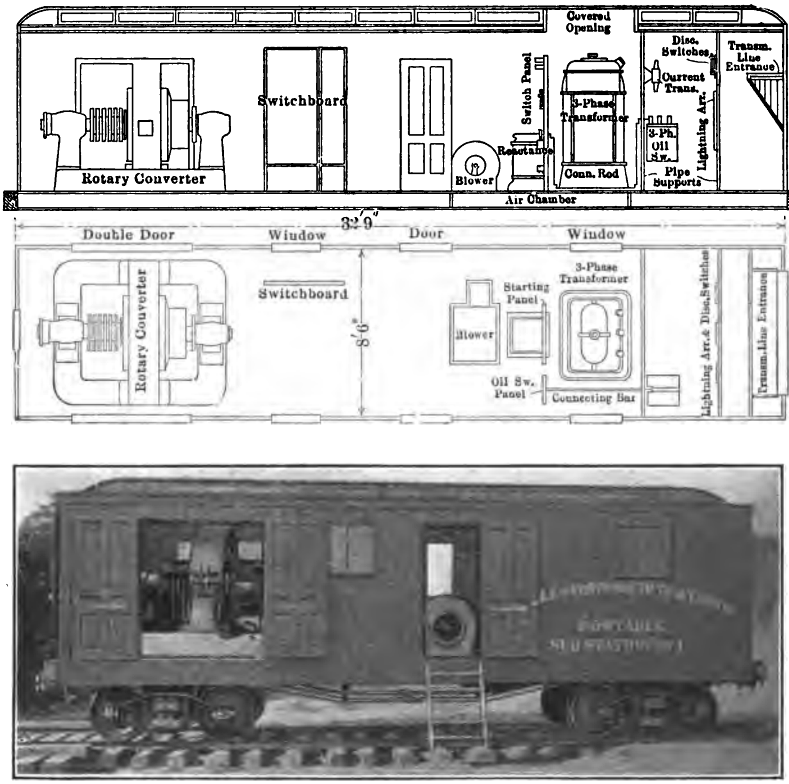


FIG. 50.

ent sections of the line. A means of meeting this local and temporary demand for power has been found in the "portable substation," Fig. 50, which usually consists of a box car with a converter, transformers, switchboard, etc., complete and ready for connection to the high tension lines at any point on the system and capable of operating in parallel with the permanent station on any desired trolley section. Such a portable station has

proved a means of providing good service under extreme conditions not only, but has protected the regular equipment from damage due to serious overload as well.

High Voltage Direct Current Substations.—Within the last few years the 1200 volt direct current railway system has been developed and some dozen interurban roads are now operating on this voltage. This increase of voltage decreases the first cost of installation as it reduces the number of substations necessary as well as the amount of distribution copper required. A more detailed comparison of its cost and advantages will be found in a later chapter.

FIG. 51.

The substation design for such a system is not materially different from that outlined above except in the case of the converting equipment. Two standard 600 volt machines, connected in series, are usually installed for this service, the negative terminal of one unit being connected to the rail while the positive lead from the second machine is carried to the switchboard bus bars and thence through 1200 volt feeder panels to the feeders and trolley. Fig. 51 shows the synchronous motor generator set used for such service in the substation of the Pittsburg, Harmony, Butler, and New Castle Railway while the wiring diagram for this station will be found in Fig. 52. It should be noted that in this installation no transformers are used although the synchronous motor of the motor generator set operates at 13,200 volts.

Single-phase Alternating Current Substations.—In systems where single-phase alternating current is supplied to the car in place of direct current there is, of course, no demand for the conversion of alternating current to direct current in the substation. On long lines, however, substations are still necessary

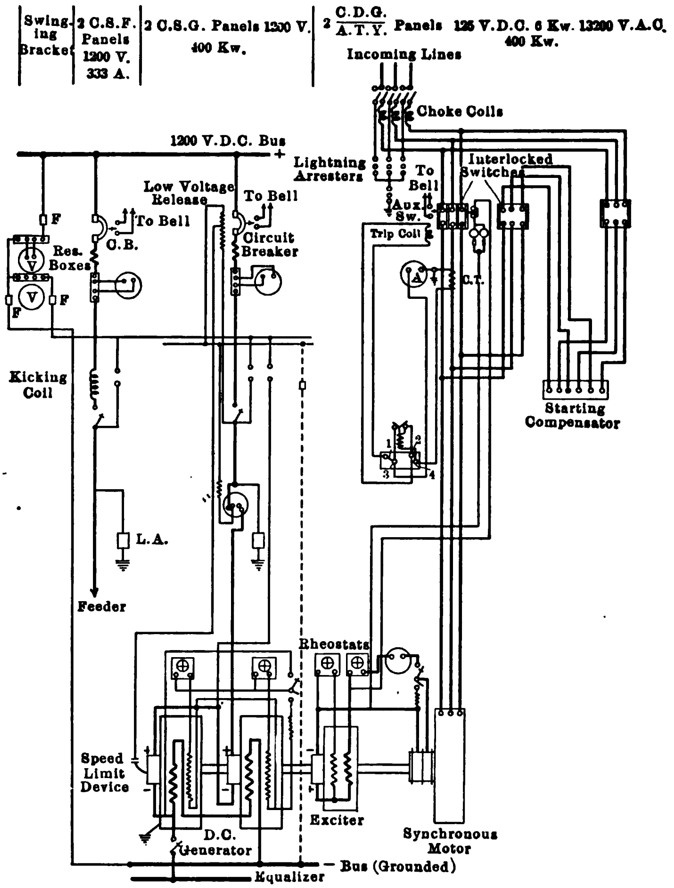


FIG. 52.

to reduce the potential of the transmission line to that suitable for the trolley, the latter voltage usually being 6,600 or 13,000 volts. Such substations involving only transformers, lightning protection, and switches, require no attendants and are therefore very small and simple in design as compared with the stations

previously considered. Automatic oil switches are usually installed in both primary and secondary circuits of the step-down transformers although in this case the time element of the automatic relay is adjusted for a greater time interval than those at the power station in order that the latter switches will open first in case of trouble. This method, which is just the reverse of that in converter substations, is adopted to avoid frequent trips to the

FIG. 53.

substation to close switches. The accompanying Fig. 53 illustrates one of the stations of this type on the Chicago, Lake Shore, and South Bend Railway which is probably the longest interurban system operating single-phase in this country.

Substation Cost.—The following working estimate prepared to cover the total cost of four substations of the 600 volt direct current type for a 63-mile interurban line in the South may be useful in determining the relative cost of substation equipment. As each station contains one synchronous converter of 300 kw., the costs may be figured on a basis of 300 kw. per station.

4 Substation buildings, @$4.00 kw	$4,800
4 Converter foundations, 150 yd. @ $8.00	1,200
4 Transformer banks, 1320 kw. @ $10.00	13,200
4 Converters, 1200 kw. @ $16.00	19,200
Freight and erection,	3,000
4 Switchboards, 4 panels each	8,800
Freight and erection	1,600
Wiring, @ $1.50 per kw	1,800
High tension switch cells	1,000
Lightning protection	2,400
Total @ $47.50 kw	$57,000

Whereas the discussion in this chapter covers the principal features of substation location and design, many special features with regard to operating costs and the function which the substation has to play in the various types of distribution systems will be considered briefly in succeeding chapters.

CHAPTER IV.

Transmission System.

The necessity for greatly detailed calculations in designing high tension transmission lines for railway systems is often exaggerated. The fact that the careful predetermination of all characteristics of such a transmission line is unnecessary, when compared with the careful study required in connection with a line for the transmission of power for lighting or even for the very high voltage long distance transmission of energy in large quantities from hydro-electric plants, will be made clear by the following outline of conditions generally pertaining to the railway system.

In the first place the close regulation of voltage is both unnecessary and impossible. The sudden variations of power demanded by cars, especially upon an interurban system, must inevitably mean variable voltage and with such voltage variation on the distribution system there is little need of the closest possible regulation on the transmission line.

Nor is the service impaired by such voltage variation as would be suicidal to the lighting substation. The motorman or passengers upon an interurban car will hardly notice a ten per cent. voltage variation, while sudden variations of 2 or 3 per cent. are to be avoided if possible in connection with incandescent lighting, particularly as the intensity of light varies throughout a greater range than the voltage. The lighting of interurban cars is of course greatly impaired by poor voltage regulation and this is one of the features that is receiving a great deal of just criticism from the traveling public. Its remedy, however, lies in making the lighting independent of trolley voltage and not by attempting to regulate the latter more closely.

The regulation of transmission lines is greatly affected by low power factor. The addition of induction motors or arc lighting systems which operate at low power factors to long distance transmission lines involves very careful design and costly regulating apparatus if lighting loads are to be successfully supplied by the same line. In many such instances synchronous motors are installed, often without direct financial return to the company,

in order that the power factor may be properly controlled. Such control is present in the railway substation in either the synchronous motor generator set or converter and with little practice the substation attendant can maintain very nearly unity power factor on the transmission line and thereby aid its regulation to a great extent.

Many of the limiting factors in high tension line design such as the pin type of insulator, corona losses, troubles introduced by wide spacing and long spans, etc., are introduced only when the voltage becomes higher and the amounts of power become much greater than those involved in the major part of the interurban transmission. In fact a census of transmission lines for railway purposes only would probably reveal the fact that an extremely small percentage of these lines are above 33,000 volts. At this voltage two parallel three-phase circuits on pin type insulators and wooden poles carrying in addition the distribution feeders and trolley brackets represent common practice. Such a line in the Middle West has for years been satisfactorily operating an interurban system 110 miles in length at 33,000 volts. In such design simple electrical and mechanical considerations are alone involved.

For the above reasons, therefore, and because of the very able treatises in complete volumes devoted to the details of this subject, an exhaustive study of transmission line design will not be attempted in these pages.

The three-phase system of alternating current transmission has been standardized almost exclusively for railway work. This is principally because polyphase apparatus is necessary for substation units in large sizes and in addition because the three-phase system requires but three-fourths the copper of the single-phase installation. Other polyphase systems, although more economical in copper in some instances, have not found favor largely because of the complication introduced by the greater number of wires. While six-phase substation apparatus was shown in the preceding chapter to be highly desirable, the possibility of its operation from a three-phase line has introduced no serious consideration of six-phase transmission. For these reasons, therefore, three-phase transmission only will be herein considered.

Mechanical Strength.—Owing to the fact that calculations of the proper size of wire for transmission lines based on Kelvin's law, voltage regulation, and carrying capacity, in most cases result in a wire too small to withstand the mechanical stresses incurred by ordinary line construction and weather conditions, the mechanical strength of the line may well be considered first and the size of wire checked in accordance with the electrical considerations later. No wires smaller than No. 4 B. & S. hard drawn copper or its equivalent in tensile strength should be used for mechanical reasons. If aluminum be used it should be remembered that for the same size aluminum weighs about 30 per cent. and has a resistance of 1.67 times that of hard drawn copper. Aluminum costs considerably less than copper for the same conductivity and melts at a much lower temperature. It also has a greater coefficient of expansion causing greater variation in sag with change of temperature. It is difficult to solder, is quickly attacked by gases in the atmosphere and has a tensile strength of approximately one-third that of copper. In spite of its many disadvantages aluminum is used to a considerable extent for line construction largely because of its low cost and light weight. Joints are made mechanically by overlapping the ends in an oval sleeve and twisting the sleeve and wire ends together without solder. On account of its large diameter for a given conductivity the total wind pressure on a line is greater and because of its low melting point it is more likely to melt apart than is copper in the event of an arc forming between wires.

The question whether one or two parallel three-phase lines shall be installed, one for the purpose of acting as a relay for the other in case of break-down is an open one and is generally decided by the personal preference of the engineer in charge. If a single line only be installed it is usually mechanically stronger and therefore better able to withstand abnormal strains. In this case the wires are spaced at the vertices of an equilateral triangle with one wire on the pole top and the two lower wires on a single cross arm. If two circuits are employed two arms are used and one circuit is installed on either side of the pole. Such construction permits repairs to be made on one of the lines with the other in operation when the voltage does not exceed 33,000 volts.

No particular specifications need be made for the poles, which are also used for the trolley span wires, feeders, and probably signal and telephone circuits as well, except that they must be sufficiently high to give sufficient clearance to the high tension wires during the period of maximum sag and that they be at least 7 in. in diameter at the top. The forces acting on the poles due to the presence of the high tension line are,

Vertical downward force due to weight of conductors with possible ice sheath and vertical component of wire tension.

Bending moment due to angle in line or with one or more wires broken.

Bending moment due to wind pressure on pole and ice sheathed wires.

Although these forces may be readily calculated by means of the fundamental laws of mechanics, it is safe to assume that there is a sufficient factor of safety with a properly constructed pole line sufficiently heavy for the trolley and feeder installation for the reason that the latter acts as a longitudinal anchor guy in case of a broken high tension wire and owing to the further fact that the possible strains on the high tension line are generally small as compared with those incurred by the feeder and trolley construction.

Electrical Considerations.—Considering the large number of railway high tension lines using No. 4 B. & S. wire, and remembering that this should be a minimum for mechanical reasons, it will probably save time in calculation to assume this size at the start. A convenient spacing for wires not exceeding 33,000 volts is 36 in. With these dimensions in mind it will be remembered that in determining the regulation of an alternating current line the impedance must be considered in place of the resistance which is used in direct current calculations. Impedance may be considered as the resultant of the resistance and the reactance of the line combined at right angles. In other words,

$$Z=\sqrt{R^2+X^2} \tag{81}$$

where Z = Impedance of line in ohms.

R = Resistance of line in ohms.

X = Reactance of line in ohms.

The reactance (X) of a transmission line is partly due to inductance (L), which in turn is dependent upon the cutting by the wire of lines of force set up by the current in the wire, and the capacity (C) which is the effect due to the wires acting as the plates of condensers with the air as a dielectric medium between. Since the formulæ for these quantities given below show that the capacity is decreased and the inductance increased as the wires are moved apart and also as the size of wire is decreased, these two functions of reactance will be seen to be opposed to one another, one neutralizing the other to some extent. Since the capacity effect is relatively small, especially on the average short line of the interurban railway operating at moderate voltage, it will be neglected in the first determination of regulation and the error introduced by such a procedure pointed out later.

As the theoretical proof of the formulæ for line inductance and capacity is beyond the scope of this book and as their methods of derivation are included in most theoretical treatises on electrical engineering they are listed below without proof.

$$C = \frac{0.0776\ l}{2 \log._{10} \frac{d}{r}} \tag{82}$$

$$L = .000322\left(2.303 \log_{10}\left(\frac{d}{r}\right) + 0.25\right)l \tag{83}$$

where L = Self inductance per wire in henries.

d = Distance between wire centers in inches.

r = Radius of wire in inches.

C = Capacity between one wire and neutral point in microfarads.

l = Length of circuit in miles.

Considering only the resistance and inductive reactance of the line at present the latter may be found from the equation,

$$X_L = 2\ \pi f L. \tag{84}$$

where X_L = Reactance due to inductance in ohms.

f = Frequency in cycles per sec.

L = Inductance from equation (83) in henries.

Tables giving such of the inductive reactance values and resistances as will be needed in railway transmission line calculations are given below.

TABLE XI.[1]

Inductive Reactance of Single Wire in Ohms per Mile.

Size wire.	Spacing inches 25 cycles.									
	24	36	48	60	72	84	96	108	120	150
350000 cm.	.235	.255	.270	.280	.290	.298	.304	.310	.315	.327
300000	.238	.258	.273	.285	.294	.301	.308	.314	.320	.330
250000	.242	.263	.278	.289	.298	.305	.313	.319	.324	.335
4/0 B & S	.248	.268	.283	.294	.303	.310	.318	.325	.329	.340
3/0	.254	.274	.289	.300	.309	.317	.324	.330	.335	.346
2/0	.259	.280	.294	.306	.315	.323	.329	.335	.341	.352
0	.265	.286	.300	.311	.321	.329	.335	.341	.347	.358
1	.271	.292	.306	.318	.327	.334	.341	.347	.352	.364
2	.277	.297	.312	.323	.332	.340	.347	.353	.358	.370
3	.283	.303	.318	.329	.338	.345	.352	.359	.364	.375
4	.289	.309	.324	.335	.344	.352	.359	.365	.370	.381
6	.300	.321	.335	.347	.356	.363	.370	.376	.381	.393

TABLE XII.[1]

Resistance of Copper and Aluminum at 70° Fahr.

Size wire.	Ohms per mile.	
	Copper.	Aluminum.
500000 cm.	.109	.176
450000	.121	.196
400000	.137	.221
350000	.156	.252
300000	.182	.294
250000	.219	.353
4/0 B & S	.258	.417
3/0	.326	.526
2/0	.411	.664
0	.518	.837
1	.653	1.055
2	.824	1.330
3	1.039	1.678
4	1.309	2.116
6	2.082	3.309

[1] Standard Handbook, Section 11, p. 40.

Since the power factor at the substation may be maintained at approximately 100 per cent. by control of the field of the synchronous converter or motor generator, such a power factor may be safely assumed in line calculation. In fact it would not introduce a serious error to neglect impedance of the line entirely and solve the problem as if for a direct current system since even the effect of line reactance may be overcome by careful regulation of the substation apparatus as explained above.

Voltage Determination.—The voltage and current per wire must now be determined. They are principally dependent upon the substation input and distance of transmission.

In deciding upon the proper voltage for the transmission line as well as in selecting electrical equipment it is necessary to take into consideration the standards established by the manufacturers. Primary substation voltages have been standardized as follows: 11,000, 19,100, 33,000, and 66,000 volts. The two lower potentials are most often used with "delta" connections while voltages of 33,000 and 66,000 are obtained with "Star" connected transformers. It should be noted that the three lower voltages bear the ratio of $\sqrt{3}$ to one another thus permitting the next higher standard voltage to be obtained by changing connections of transformers from "delta" to "star." For a rough selection of the voltage to be first used for calculation, 1000 volts per mile of transmission are often used. As local conditions enter into the problem to a marked degree, and since it is almost impossible to express intelligently in equation form all the factors entering into the selection of the proper voltage from the standpoint of regulation, first cost, and economical operation, it seems advisable to select two of the nearest standard voltages by the above rule and compare the resulting calculated data of the two cases before finally determining upon the best operating voltage.

Regulation.—The transmission line calculations are usually based upon the combined substation inputs supplied by a single line at full rated load although, if the number of substations be large, it may be found from a study of their load curves that their maximum loads do not occur simultaneously and that the total demand on the transmission line may be considerably below the summation of the substation ratings. The rated output of the

substation transformers was found in Chapter III equation (80). The input to the station may be obtained from the above by dividing the output of all transformers by the transformer efficiency which may be safely assumed for large transformers at full load as 98 per cent.

The current per wire on the transmission line is therefore

$$I_w = \frac{\text{Kw. x } 1000}{\sqrt{3}\, E \cos \phi} \tag{85}$$

where I_w = Current per wire in amperes.
Kw = Substation input in kilowatts.
E = Voltage between wires at substation.
$\cos \phi$ = Power factor of load at substation.

For this calculation ($\cos \phi$) is taken as unity as explained above.

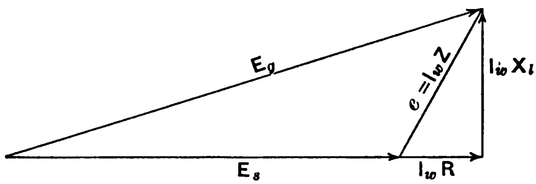


FIG. 54.—Vector diagram for transmission line regulation unity power factor.

The impedance of the transmission line may now be found from equation (81) if values of reactance and resistance from Tables XI and XII for No. 4 B & S wires spaced 36 in. apart be substituted. The voltage drop on the line is

$$e = I_w Z \tag{86}$$

These relations including the generator voltage (E_g) are shown in Fig. 54 from which the value of E_g may be derived.

$$E_g = \sqrt{(E_s + I_w R)^2 + (I_w X_L)^2} \tag{87}$$

where (E_s) represents substation voltage between wire and neutral or $\frac{E}{\sqrt{3}}$

$$\text{Reg} = \frac{E_g - E_s}{E_s} \tag{88}$$

If less than unity lagging power factor be assumed as in the case of an induction motor generator set for example, other conditions remaining the same, a larger current (I'_w) would have

resulted from equation (85) and the voltage diagram would appear as in Fig. 55, the resulting generator voltage being

$$E'_g = \sqrt{(E_s \cos\phi + I'_w R)^2 + (E_s \sin\phi + I'_w X_L)^2} \qquad (89)$$

As before, the percentage regulation may be obtained from the equation

$$Reg' = \frac{E'_g - E_s}{E_s} \qquad (90)$$

If the regulation from either equation (88) or (90) is unreasonably high, a suitable value, say 10 per cent., may be substituted back into the equation and corresponding values of E_g or E'_g found

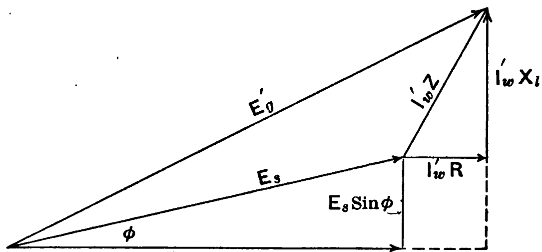


FIG. 55.—Vector diagram for transmission line regulation lagging power factor.

from which the correct value of (R) may be calculated by means of equation (87) or (89) and the proper size of wire obtained from the wire table.

As a concrete illustration of these two approximate methods of obtaining regulation, assume the following conditions,

Substation input = 1500 kilowatts.
Power factor = 100 per cent.
Length of line = 50 miles.

Using No. 4 wire and a substation voltage of 33,000, there results,

$R = 1.309 \times 50 = 65.4$ ohms.

$X_L = 0.31 \times 50 = 15.5$ ohms.

$$E_s \text{ per terminal} = \frac{33000}{\sqrt{3}} = 19{,}100 \text{ volts}$$

$$Z = \sqrt{(65.4)^2 + (15.5)^2} = 67 \text{ ohms.}$$

$$I_W = \frac{1{,}500{,}000}{33{,}000\sqrt{3}} = 26.2 \text{ amp.}$$

$$E_g = \sqrt{(19{,}100 + 26.2 \times 65.4)^2 + (26.2 \times 15.5)^2} = 20{,}820 \qquad (87)$$

$$\text{Reg} = \frac{20{,}820 - 19{,}100}{19{,}100} = 9 \text{ per cent.} \qquad (88)$$

Now suppose the power factor to be lowered to 85 per cent. by low field excitation of synchronous apparatus or the operation of an induction motor generator set.

$$I'_w = \frac{1{,}500{,}000}{33{,}000\sqrt{3} \times 0.85} = 30.9 \text{ amp.} \qquad (85)$$

$$E'_g = \sqrt{(19{,}100 \times .85 + 30.9 \times 65.4)^2 + (19{,}100 \times 0.527 + 30.9 \times 15.5)^2} = 20900 \qquad (89)$$

$$\text{Reg}' = \frac{20{,}900 - 19{,}100}{19{,}100} = 9.43 \text{ per cent.} \qquad (90)$$

Both the regulation for 85 per cent. power factor and unity power factor are sufficiently small for railway service and the conditions of size of wire, voltage, spacing, etc., may be tentatively decided upon and checked further with regard to Kelvin's law, carrying capacity, etc., as explained under "Distribution System."

Capacity Effect.—Since, however, the capacity has been entirely neglected in the above calculations, the error introduced by such omission should at least be pointed out.

As previously explained, the line wires act as plates of a condenser and thus draw a leading "charging" current from the power house just as an infinite number of small condensers would do if connected in parallel across the line wires throughout their entire length. As such a uniform distribution of capacity involves a constantly changing charging current, power factor, and voltage throughout the entire length of the line, which condition can be represented only by a rather involved mathematical equation, it has been shown by Steinmetz[1] that this capacity effect may be represented sufficiently accurately by locating one-sixth of the total capacity at either end and two-thirds in the middle of the line. In fact, little error is introduced if the entire capacity is considered in parallel with the line at either the generator or receiver end. Adopting the latter assumption the equations below show the method of derivation of the values in Table XI and the calculation of charging current for any assumed length of line, voltage, and wire spacing.

[1] Alternating Current Phenomena by Dr. C. P. Steinmetz.

The values of charging current in Table XIII which are dependent upon a voltage between the line wires and the neutral point of 100,000 volts for a single mile of line at 25 cycles frequency and a given spacing are obtained by substitution in the formula (82).

For example, assuming the conditions of the transmission problem above

$$C = \frac{.0776}{2 \log_{10}\left(\frac{36}{.102}\right)} = 0.0153 \text{ microfarad.} \tag{83}$$

between 1 mile of No. 4 wire and neutral with 36 in. spacing

$$I_c = \frac{2\,\pi f C E}{10^6} \tag{91}$$

If I_c = Charging current in amperes per mile at 100,000 volts
f = Frequency in cycles per sec.
C = Capacity in microfarads per mile.
E = 100,000 volts.

$$I_c = \frac{2\,\pi \times 25 \times 0.0153 \times 100{,}000}{10^6} = 0.239 \text{ amp.} \tag{91}$$

TABLE XIII.

Charging Current of Single Wire in Amperes per Mile per 100,000 Volts, 25 Cycles.

Size wire stranded.	Spacing in inches.									
	24	36	48	60	72	84	96	108	120	150
350000 cm.	.329	.300	.283	.270	.261	.254	.248	.243	.239	.230
300000	.323	.295	.278	.267	.258	.250	.245	.240	.236	.227
250000	.316	.290	.274	.262	.253	.246	.241	.236	.232	.224
Solid 4/0 B & S	.301	.278	.262	.253	.243	.239	.232	.228	.224	.210
3/0	.295	.272	.257	.245	.239	.234	.228	.224	.220	.212
2/0	.287	.265	.251	.242	.232	.228	.224	.220	.217	.209
0	.279	.261	.246	.237	.229	.225	.220	.217	.212	.206
1	.275	.251	.242	.229	.223	.220	.217	.212	.209	.203
2	.268	.250	.237	.226	.221	.217	.212	.209	.206	.199
3	.264	.246	.229	.225	.217	.212	.209	.206	.203	.196
4	.255	.239	.226	.220	.214	.209	.206	.203	.200	.193
6	.245	.231	.220	.212	.204	.201	.198	.195	.191	.189

This value will be found in Table XIII opposite No. 4 wire with 36 in. spacing.

The charging current for any other voltage (E′) between wire and neutral and for any other length of line (l) is of course

$$I'_c = \frac{2\ \pi f C E' l}{100{,}000 \times 10^6} \tag{92}$$

or

$$I'_c = \frac{\text{Table value} \times l \times E'}{100{,}000} \tag{93}$$

Again considering the concrete illustrative problem at unity power factor the charging current for the line is

$$I'_c = \frac{0.239 \times 50 \times 19{,}100}{100{,}000} = 2.28 \text{ amp.} \tag{93}$$

It will be seen therefore that the charging current with this particular load and design of line is quite an appreciable percentage (8.7 per cent.) of the full load unity power factor current. The charging current might be decreased somewhat by separating the wires. As this current is independent of load its percentage will decrease of course as the load increases.

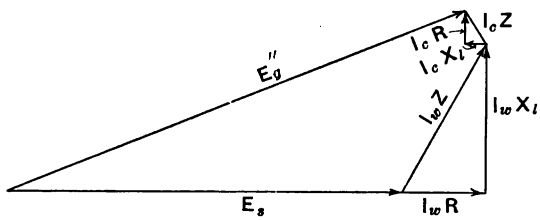


FIG. 56.—Vector diagram for transmission line regulation with charging current.

In refiguring the regulation this time taking the charging current into account, it must be remembered that this current leads the voltage at the substation (E_s) by 90 degrees. The vector diagram of voltages is therefore represented by Fig. 56 where the direction of the charging current vector and therefore of the vector of resistance drop due to charging current (I_cR) is vertical and the reactance drop due to charging current (I_cX_L)

horizontal since (E_s) is horizontal. The generator voltage (E''_g) may be seen from the geometry of the diagram to be

$$E''_g = \sqrt{(E_s + I_W R - I_c X_L)^2 + (I_W X_L + I_c R)^2} \qquad (94)$$

which is obviously less than (E_g), equation (87), since the charging current tends to neutralize the effect of line inductive reactance, thereby reducing the regulation to the value

$$\text{Reg}'' = \frac{E''_g - E_s}{E_s} \qquad (95)$$

Substituting the numerical data of the above problem

$$E''_g = \sqrt{(19{,}100 + 26.2 \times 65.4 - 2.28 \times 15.5)^2 + (26.2 \times 15.5 + 2.28 \times 65.4)^2} = 20{,}760 \text{ volts} \qquad (94)$$

$$\text{Reg}'' = \frac{20{,}760 - 19{,}100}{19{,}100} = 8.7 \text{ per cent.} \qquad (95)$$

A similar diagram might be drawn and the regulation calculated showing the effect of charging current with low initial lagging power factor by adding the triangle of charging current fall of potential to the diagram, Fig. 55, with the vector ($I_c R$) leading (E_s) by 90 degrees.

Comparing the regulation found by taking charging current into account equation (95), with that which neglected that particular effect equation (88) the error will be seen to be

$$\text{Error} = \frac{9 - 8.7}{8.7} = 3.5 \text{ per cent.}$$

which may safely be neglected in most railway work, especially as the approximate method gives the highest and therefore the most conservative estimate of the regulation.

It is believed that the above considerations, together with some of the suggestions regarding high tension line protection and wiring considered in Chapter III cover the more important factors involved in the design of high tension lines for railway service. For further details of construction and for theoretical consideration of the limiting factors which enter into exceptionally high voltage installations reference should be made to the many complete works on these subjects.

Estimates of construction costs on both distribution and transmission systems have been purposely omitted owing to the fact that the cost of copper is the dominating factor in these portions of the railway system and such cost is so variable a quantity that estimates or costs of previous installations have to be used with great caution when applying them to proposed systems.

CHAPTER V.

POWER HOUSE LOCATION AND DESIGN.

Whereas the complete analysis of this subject would require a volume of generous dimensions, a few of the salient features to be borne in mind by the engineer in charge of the planning and construction of a complete electric railway system may well be suggested.

Location.—The determination of the proper location for the power house from the one standpoint of most economical transmission of power to substations is made in a manner similar to that described for the location of substations, Chapter III, except that in this case the various loads are the full load ratings of the various substations supplied from the power station divided by the transmission line efficiency. The center of gravity of such loads spaced at the proper distance between substations locates the power station.

With the power station, however, many other factors have to be considered before its location can be decided. The relative weight of these factors will vary with local conditions but they are listed below in the order of importance as nearly as can be determined for the average case.

The question of cheap coal supply to the steam power station is all important. In spite of this fact it is often neglected or given little thought, especially in the case of small stations, where it is often believed that coal may be drayed to the station at relatively small expense. The growth of traffic and competition with steam lines unwilling to cooperate with respect to the installation of spur tracks or track connections with the interurban road, have in a number of instances seriously embarrassed small interurban systems or at least prevented the power station reaching a reasonable cost of energy output. The station should be located on a railroad siding, or better, if the proposed line is in the vicinity of a navigable river, many of the other factors entering into the location of the station may be waived in order to locate the sta-

tion at a point where the coal may be deposited in the bunkers directly from the coal barges. A notable example of such location is that of the proposed power station of the southern interurban line previously referred to which is distant 3 miles from the line of the road in order that it may be located where ocean going coal barges may be docked.

The question of an adequate and reasonably soft water supply for boiler feed and condensing purposes should receive second consideration. In sections of the country where it is necessary to depend upon artesian well water for boiler feed it is either necessary to install rather expensive water softening plants or submit to a high maintenance and depreciation charge on boilers with considerable risk of service interruption. The marked loss of efficiency and corresponding increase in cost of generated power if a condensing plant is occasionally forced to operate non-condensing is to be avoided if possible, especially in the case of steam turbines, whose principal advantage over the reciprocating engines is the increased economy at high degrees of condenser vacuum. Gravity intakes of pipe or concrete tunnel construction are preferable to long pipe suction lines and considerable expense is warranted in bringing a generous supply of cold pure water into the cold wells of power stations and in providing a free discharge of the hot well to waste under all conditions of water level in flood season and drought. Especially should the purity of condensing water be assured with the surface type of condenser used to such an extent with steam turbines.

Building foundations, especially for the heavy machinery of the station, should be unquestioned in their stability. Many instances may be quoted in which the saving of first costs of test borings or real estate was attempted at the later expense of the settling of foundations, carrying with it numberless construction and operating difficulties. Nor is it sufficient to determine the fact that there is good subsoil below a proposed station location. The depth of excavation necessary to reach this subsoil and the consequent cost of foundations should be carefully learned from preliminary test borings.

The power station often acts in the capacity of one of the substations on the line supplying the high tension lines to other sub-

stations not only, but transforming a portion of the generated electrical energy into a form adaptable to the nearby trolley and feeder system. This plan can only be carried out when the power station is located very near the right of way of the railroad as the low voltage of the distribution system is not designed for transmission to any considerable distance.

The cost of real estate is a very obvious factor in the determination of power station site. With an interurban road the center of gravity of the load would naturally remove the station from the terminal cities where the cost of real estate is probably higher than at any other point on the line, but the operation of the line or a portion of it at least by the existing power companies of the terminal cities often involves power station additions or new locations where real estate is high in cost. This sometimes leads to the double-decking of stations with turbine rooms above the boilers. This construction has the further advantage of short connections between boilers and turbines.

A feature often overlooked in the selection of a site is the convenience of a location near the car house and shops. Such a location often prevents a duplication of shop equipment and the tools, supplies, and even labor which may be used in common, especially in case of emergency, by both power station and car shops is surprising. Such cooperation between the departments of a large railway system must result in better service and improved economy of operation.

Closely allied with the above is the necessity of locating the station at a point where employees and preferably some, if not all of the heads of departments, are willing to reside. Especially in the emergencies which are only too frequent in railway operation is this of great value to the company.

Within the city limits the question of smoke nuisance sometimes has a bearing upon the problem, but as expert firing and special design of furnaces with the possible instal'ation of smoke consuming devices, if efficient ones can be obtained, reduce this trouble to an unobjectionable minimum, this factor has little weight in placing a station.

Design.—The building which is to house the generating equipment should be designzed for that purpose primarily, without too

much thought for architectural beauty. Too many small roads have elaborate stations which are paying little or no returns on the investment and are found wanting in highly efficient equipment and attendance. Substantial brick or concrete buildings with generous basements for auxiliaries, piping, and wiring are necessary. They should be provided with plenty of head room for crane operation and generously lighted. Such a power station interior is illustrated in Fig. 57. This building is constructed of concrete blocks and is well planned to house the single-phase generating equipment of the Chicago, Lake Shore, and

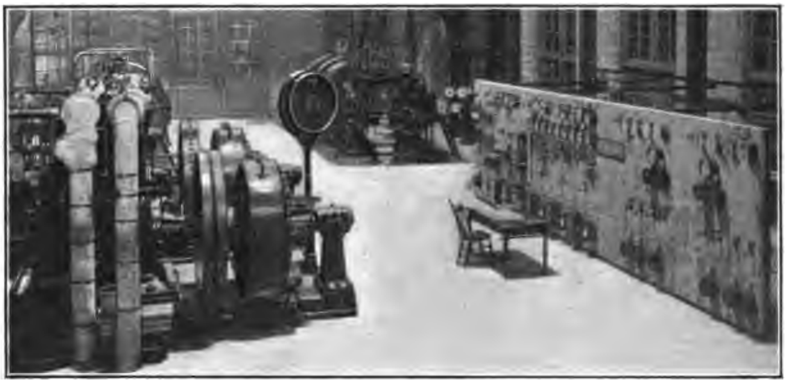


FIG. 57.

South Bend Railway, at Michigan City, Indiana. This photograph was taken at night by means of the mercury vapor lamps used for illumination.

The costs of power station buildings cover a wide range, but for a fairly large modern station sufficiently commodious to accommodate all necessary machinery without overcrowding a figure of from $3.25 to $3.50 per square foot of floor area should be allowed.

The question of vibration and foundation construction should be given very careful attention, especially where high speed reciprocating machinery is employed. Vibration has caused serious difficulties even in turbine stations of the double-decked type with the turbines located on the second floor. Care should be taken also to plan for future extensions in the construction of the building, many stations being carried to the extreme of closing

one end with temporary corrugated iron construction which may be readily torn down as extensions are made.

Capacity.—In determining the total output of the station, methods similar to those used in the case of the substation are employed with due consideration being given to the "diversity factor." This factor, which has only recently been given its proper attention by operating companies, may be defined as the ratio of the maximum load on the station to the summation of the maximum loads of the various substations. That is to say, since the maximum loads come on the various substations at different times, the capacity of the power station may be considerably less than the sum of the substation capacities. The only accurate way, therefore, to determine the probable load on the power station is to plot the summation of all the substation load curves against the same abscissæ of time and divide the average and maximum values of this load curve by the substation and transmission line efficiency. Such a load curve will involve, aside from its momentary fluctuations, two or more well defined peaks which must be taken into account in determining the number of units to be installed. Reference to Chapter III will recall the method of subdividing the total load into the proper number of generating units which is equally applicable to the power station, with the exception that extensive subdivision into a relatively large number of small units involves more small duplicate auxiliary equipment in the case of the power station incurring correspondingly increased maintenance and attendance charges. The generating equipment of the average interurban power station will not include more than three units, one of which is often equal in capacity to the other two combined.

Choice of Prime Movers.—When the transmission of power from a nearby water privilege with its relatively low cost of energy is not possible, the following methods of driving prime movers are usually open for consideration in laying out a new power station.

1. Reciprocating steam engines.
2. Steam turbines.
3. Gas engines.
4. Various combinations of the above.

The relative advantages of the various prime movers and their

combinations are best set forth by quoting Table XIV published by Mr. H. G. Scott. In this table the various maintenance charges of each type of installation are not only given their proper weights but the variation of the individual charges in changing from one prime mover to another are very clearly shown. In addition, the relative investments necessary for the various types of plant are compared with that for the reciprocating steam engine plant as 100 per cent.

TABLE XIV.[1]

DISTRIBUTION OF MAINTENANCE AND OPERATION CHARGES PER KW. HOUR.

Maintenance.	Recip. engines.	Steam turbines.	Eng. and turbines.	Gas engines.	Gas engines and turbines.
Engine room mechanical	2.57	0.51	1.54	2.57	1.54
Boiler or producer room	4.61	4.30	3.52	1.15	1.95
Coal and ash handling, apparatus	0.58	0.54	0.44	0.29	0.29
Electrical apparatus	1.12	1.12	1.12	1.12	1.12
Operation					
Coal and ash handling labor	2.26	2.11	1.74	1.13	1.13
Removal of ashes	1.06	0.94	0.80	0.53	0.53
Dock rental	0.74	0.74	0.74	0.74	0.74
Boiler room labor	7.15	6.68	5.46	1.79	3.03
Boiler room oil, waste, etc	0.17	0.17	0.17	0.17	0.17
Coal	61.30	57.30	46.87	26.31	25.77
Water	7.14	0.71	5.46	3.57	2.14
Engine room mechanical labor	6.71	1.35	4.03	6.71	4.03
Lubrication	1.77	0.35	1.01	1.77	1.06
Waste, etc	0.30	0.30	0.30	0.30	0.30
Electrical labor	2.52	2.52	2.52	2.52	2.52
Relative cost of maintenance and operation.	100.00	79.64	75.72	50.67	46.32
Relative investment in per cent.	100.00	82.50	77.00	100.00	91.20

Attention should be called to the fact that companies that have been operating railway power stations with reciprocating engines are realizing the marked economy which can be obtained by introducing low pressure turbines between the low pressure cylinders of the engines and condensers and many such combination engine and turbine stations are now in operation. The output of a condensing engine may be increased from 20 to 25 per cent. in this way with but little extra space occupied and usually without building additions.

[1] Power Plant Economics by H. G. Scott, A. I. E. E., 1906.

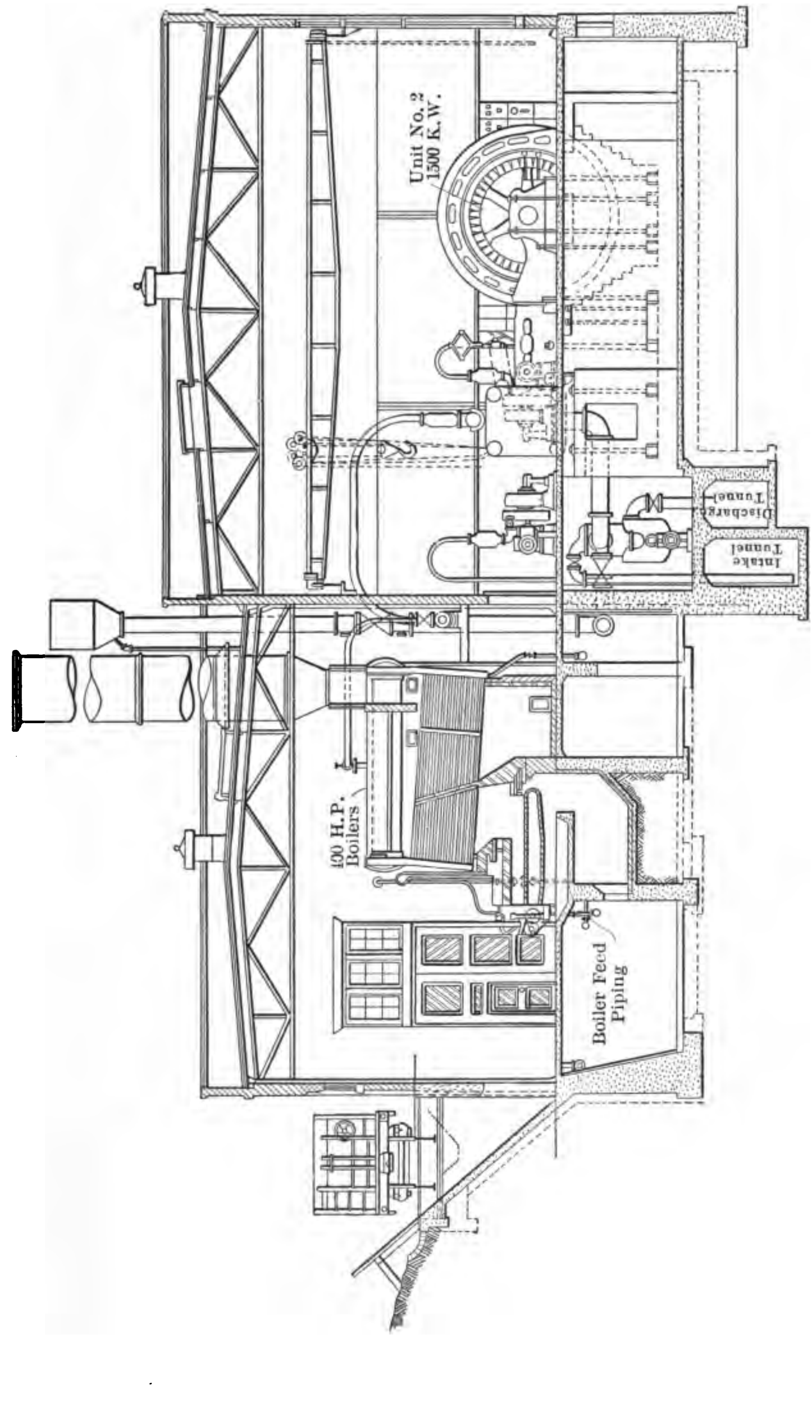

Unit No. 2
1500 K.W.
400 H.P.
Boilers
Boiler Feed
Piping
Discharge
Tunnel
Intake
Tunnel

FIG. 58.

The status of low pressure turbine development may perhaps be best judged from the summary of the report of the Committee on Power Generation of the American Electric Railway Association in 1910 which is quoted below as follows.

"In general, the installation of low pressure turbines may be recommended wherever there are good engines installed, or in the case of a new installation where the load factor and the coal cost are high. In plants having a large installation of a good type of reciprocating engine the low pressure turbine may be added at a total cost, including new condenser, auxiliaries, foundations, piping, etc., of not to exceed $25.00 per kilowatt, thus bringing down the average overall investment per kilowatt of the entire plant and so reducing the fixed charges per kilowatt-hour."

In deciding whether steam turbines or engines shall be installed the question of steam economy naturally receives first consideration. While comparative tests under exactly similar conditions have probably never been made and although it is necessary to make some assumptions in order to compare fairly the test results where operating conditions vary slightly, the following table from Kent's Mechanical Engineer's Handbook will probably compare the two units with regard to economy as well as any. These values refer to a 600 h. p. horizontal turbine operating with saturated steam at 150 lb. pressure and 28 in. vacuum and an 850 h. p. compound engine. These sizes of units are such as are often found in interurban power stations.

TABLE XV.

COMPARATIVE STEAM ECONOMY OF TURBINE AND COMPOUND ENGINE.

Per cent. full load.	41	75	100	125	Avg. 85 per cent.
	Pounds water per brake h. p.				
600 h. p. turbine............	13.62	13.91	14.48	16.05	14.51
850 h. p. compound engine....	13.78	13.44	13.66	17.36	14.56

A study of this table as well as other tests under nearly identical conditions indicates that there is little choice between the two units from the standpoint of economy alone.

The turbine seems to be the unit most often selected at the present time, however, probably because of its advantages over the compound engine with regard to first cost, space occupied, uniform rotation, freedom from vibration, low cost of foundations, etc.

Steam Turbine.—If the steam turbine be decided upon the following items should be given particular attention in writing the specifications, in addition to the usual requirements of workmanship, grade of raw material, shipment, etc. Values will be substituted for a particular 1500 kw. specification in order that the requirements may be of more value for reference.

Rating, 1500 kw. 2300 volts, 3-phase, 60 cycles.

Multistage, condensing.

Steam pressure, 150 lb.

Back pressure, 2″ referred to barometric pressure of 30″ at 32° F.

Superheat, 100° F.

Excitation, 125 volts.

Full load temperature rise at unity power factor, rated voltage, 40° C. corrected to room temperature of 25° C.

Overload temperature rise, 125 per cent. load, rated voltage, unity power factor for 2 hr. 55° C., corrected to room temperature of 25° C.

Momentary overload of 100 per cent. at rated voltage and unity power factor without injury.

Economy expressed in lb. steam per kilowatt hour.

Load per cent.	Economy.
50	20.7
75	18.9
100	18.0
150	19.0

Speed regulation at end of heat run, speed rise when unity power factor full load is suddenly thrown off shall not exceed 4 per cent. of normal full load speed. When

such load is gradually applied the speed variation shall not exceed 2 per cent. of normal full load speed.

Voltage regulation at end of heat run when load is thrown off suddenly shall not exceed 188 volts.

Insulation test shall be applied after heat run of 5000 volts alternating current for 1 min. between armature coils and surrounding conducting material and 1500 volts alternating current for 1 min. between field winding and surrounding conducting material.

A non-condensing run shall be made with rated load, power factor, voltage, steam pressure, and superheat against atmospheric pressure.

Vibration.—The units shall operate smoothly and without undue vibration and noise under all conditions, and all revolving parts shall be accurately balanced.

Centrifugal Stresses.—The revolving field shall be sufficiently strong to resist for 1 min. without injury the centrifugal stresses produced by 20 per cent. excess of speed with armature and field circuits open.

Steam Engine.—The features of particular importance in the steam engine specifications are found listed below, although these specifications do not refer to an engine for railway service.

Type, horizontal, simple, side crank, designed to run "over."

Non-condensing.

Rating, 375 h. p. at most economical cut-off, at specified steam pressure, back pressure, and normal speed.

Service, left hand direct connection to 250 kw. 2200 volt, 3-phase, revolving field alternator.

Speed, 200 r. p. m.

Steam pressure to be 125 lb. dry steam at throttle.

Back pressure to be 10 lb.

Superheat, none.

Overload, 50 per cent. for 2 hr., momentary overload of 100 per cent. without injury.

Economy expressed in lb. steam per indicated h. p. hr.

Speed regulation shall not exceed 1 1/2 per cent. of nor-

mal speed when full load is suddenly thrown on or off. The engine shall be designed to operate in such a manner that the alternating current generator to which it is

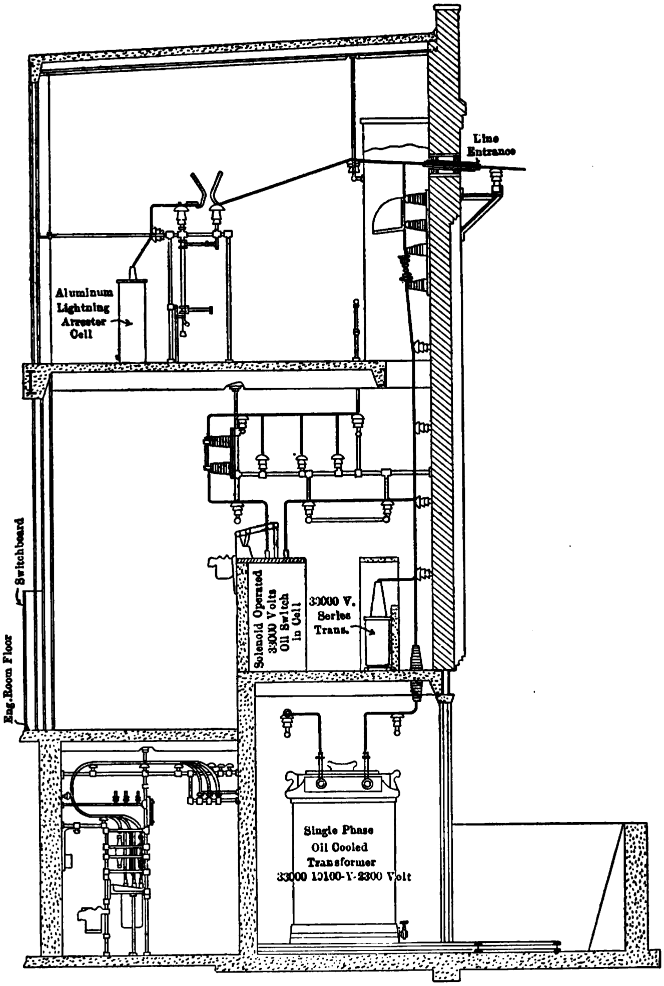


FIG. 59.

connected will operate successfully in parallel with other alternators of like general type.

Generator.—The consideration of the relative advantages of engine and turbine was purposely taken up first in order that the

necessity of installing a generator might be determined. If the steam engine be selected the alternating current direct connected generator will find a place in the power station equipment.

It is of course necessary to know the generator efficiency in order to determine the brake horse power rating of the engine, the latter being found from the following equation

$$\text{Eng. brake h. p.} = \frac{\text{Gen. output in kw x 1.34}}{\text{Gen. Effy.}} \qquad (96)$$

It is not only unnecessary but inadvisable to specify too close regulation for alternators in railway service. That the regulation need not be close has already been explained in connection with the transmission line design. In addition to that fact, however, it will be remembered that if close regulation be not required, the reactance and armature reaction of the alternator may be greater. This tends to protect the machine under the heavy overloads and short circuits to which it is likely to be subjected in railway service by lowering the voltage and therefore the short circuit current of the armature. The latter type of machines also has the further advantage of being able to keep in synchronism with one another more readily than those of better voltage regulating qualities. This is another valuable feature in railway power station operation.

The specifications for such a machine are materially the same as for the generator portion of the turbine previously outlined, with the exception that the speed is reduced to from 100 to 150 r. p. m., and in some installations of small capacity a belted exciter is provided for each generator.

Transformers.—The step-up transformers in the power station are identical with those discussed in detail in Chapter III, the low tension winding becoming the primary in this case. As in the case of the substation if the transmission line voltage does not exceed 13,000 volts, the generator armatures may be wound for full voltage and the transformers omitted.

Transformer specifications should include the rating, frequency, primary and secondary voltages, type, *i. e.*, whether oil, air, or water cooled, temperature rise (50° C.) on full load, provision for 50 per cent. overload without undue heating for 2 hr., efficiency,

power factor of load, insulation test, regulation, etc. Such transformers as would be used in power station service might be expected to have a regulation of 1.2 per cent., a full load efficiency of 98 per cent. or slightly more, and withstand a 10,000 volt insulation test for a 2200 volt rating.

Switchboard.—This portion of the power station equipment is not materially different from that described in connection with substation design and that portion which may be installed to control substation apparatus in the power station is, of course, identical therewith.

Above 13,000 volts and often below that voltage the board is of the remote control type with switches and usually cables and transformers as well, located in fire-proof brick or concrete cells. No protective device is installed between the generators and the bus bars, although the out-going transmission lines are protected with time limit relays, lightning arresters, and choke coils. For the purpose of synchronizing generators and in order to balance the loads properly between the various machines operating in parallel, the generator panels are often equipped with auxiliary circuit (125 volt) control devices for regulating the governors and thereby the speed of the prime movers.

Exciters.—Although the individual alternators are occasionally provided with separate belt-driven exciters especially in small installations, it is customary to provide a steam-driven and usually a motor-driven exciter set, the former being necessary in starting a plant. As a considerable amount of 125 volt direct current power is used about the station for auxiliary control circuits, etc., the exciters should be considerably larger than the combined demands of all alternator fields which they are called upon to supply. In selecting the exciter capacity it should also be borne in mind that the generators at low power factor require considerably increased excitation to maintain normal voltage at full load and the exciter should, therefore, be sufficiently large to supply this demand. As an additional protection against failure of excitation current which is the back bone of the power plant, storage batteries are often "floated" on the 125 volt bus bars, ready to supply energy to the field windings in case of failure of the exciters.

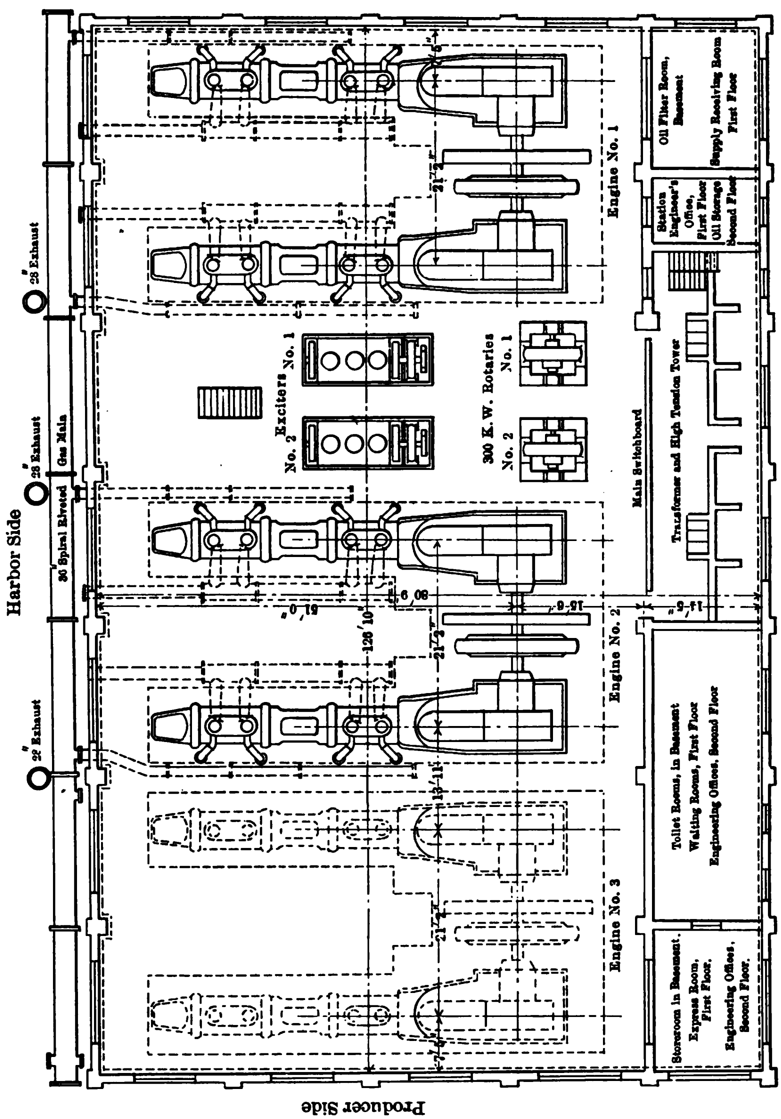

Harbor Side
22" Exhaust
28" Exhaust
28" Exhaust
36 Spiral Riveted
Gas Main
Exciters
No. 1
No. 2
300 K. W. Rotaries
No. 1
No. 2
Engine No. 1
Engine No. 2
Engine No. 3
Main Switchboard
Transformer and High Tension Tower
Oil Filter Room, Basement
Supply Receiving Room First Floor
Station Engineer's Office, First Floor
Oil Storage Second Floor
Toilet Rooms, in Basement
Waiting Rooms, First Floor
Engineering Offices, Second Floor
Storeroom in Basement.
Express Room, First Floor.
Engineering Offices, Second Floor.
128' 10"
61' 0"
21' 2"
15' 6"
11' 6"
13' 11"
Producer Side

FIG. 60.

Condensers.—As most railway power stations are operated condensing, especially when turbines are installed, the various types of condensers must be compared and a selection made of the most suitable for the purpose at hand. Condensers may be readily subdivided into three classes.

Jet condensers are designed to spray the condensing water into the steam as it comes from the low pressure cylinder of the engine, the steam coming in direct contact with the water. This type is extremely simple and cheap in first cost but in cases where the condensing water is unsuitable for boiler feed and water for the latter purpose is expensive, the jet condenser is uneconomical by reason of its wasting the condensed steam which might otherwise be used again in the boilers. The heat in the exhaust steam is also lost in this case. Pumps are provided with the condenser for supplying water and extracting air and water from the condensing chamber and thereby maintaining a vacuum. The former pump in large installations is usually of the centrifugal type.

Barometric condensers depend upon the principle that atmospheric pressure will maintain a column of water 34 ft. in height in the tail pipe of the condenser between the condenser head and the hot well. This necessitates mounting the condenser chamber 34 ft. above the hot well which often brings this chamber above the roof of the power house. The exhaust steam from the engine is discharged into this chamber and two pumps discharge water into and extract air from this chamber respectively. The vacuum is maintained by the syphon action of the column of water while simply the air which is entrained in the condensing water is removed by the air pump and the vacuum thereby improved. This type of condenser is intermediate between the other two types in expense but is usually capable of maintaining a better vacuum than the jet type. It is subject to the same disadvantages from the standpoint of feed water economy as the jet condenser.

Surface Condenser.—This condenser is the most expensive of the three types, involving as it does a series of tubes mounted within a cast iron shell, the condensing water circulating through the tubes and the steam entering and being condensed in the outside shell. As the condensed steam and condensing water

do not come in contact with one another the former may be used again as feed water and its initial heat used to advantage. Air and water circulating pumps are used as in the previous types. Whereas a better vacuum can be obtained with a surface condenser its maintenance and tube depreciation are high. It is not in extensive use, therefore, except with steam turbines where the slight gain in vacuum is of greatest importance.

The amount of water required for condensing purposes and therefore the size of condenser and piping necessary are readily calculated from the thermodynamic equation

$$W=\frac{H-h}{T-t} \qquad (97)$$

where W = Weight of condensing water in pounds.
H = Total heat in steam at the pressure corresponding to exhaust.
h = Heat in water at temperature of air pump discharge.
T = Temperature of discharged condensing water in degrees Fahrenheit.
t = Temperature of the entering condesing water.

The above values may be readily obtained from the steam tables but a rough approximation of (W) may be made by assuming average values of the above units as follows:

$$W=1150,\ h=120,\ T=110,\ \text{and}\ t=70$$

Whence

$W=\dfrac{1150-120}{40}=25.8$ lb. water necessary to condense each pound of steam.

Total water necessary per h. p. hr. is

$W_h = W$ x (Eng. economy in pounds steam per h. p. hr.) (98)

Multiplying by the rated indicated h. p. of the engine the condensing water in pounds per hour is determined.

It is customary to use a factor of safety above this figure and while 30 lb. of water per h.p. hour is a figure often quoted, many engineers install condensers and pumps on the basis of 40 lb. water per h. p. hour. In writing specifications for condensers it is the usual practice to refer to the water rate of the engine, its operating pressures and the probable water temper-

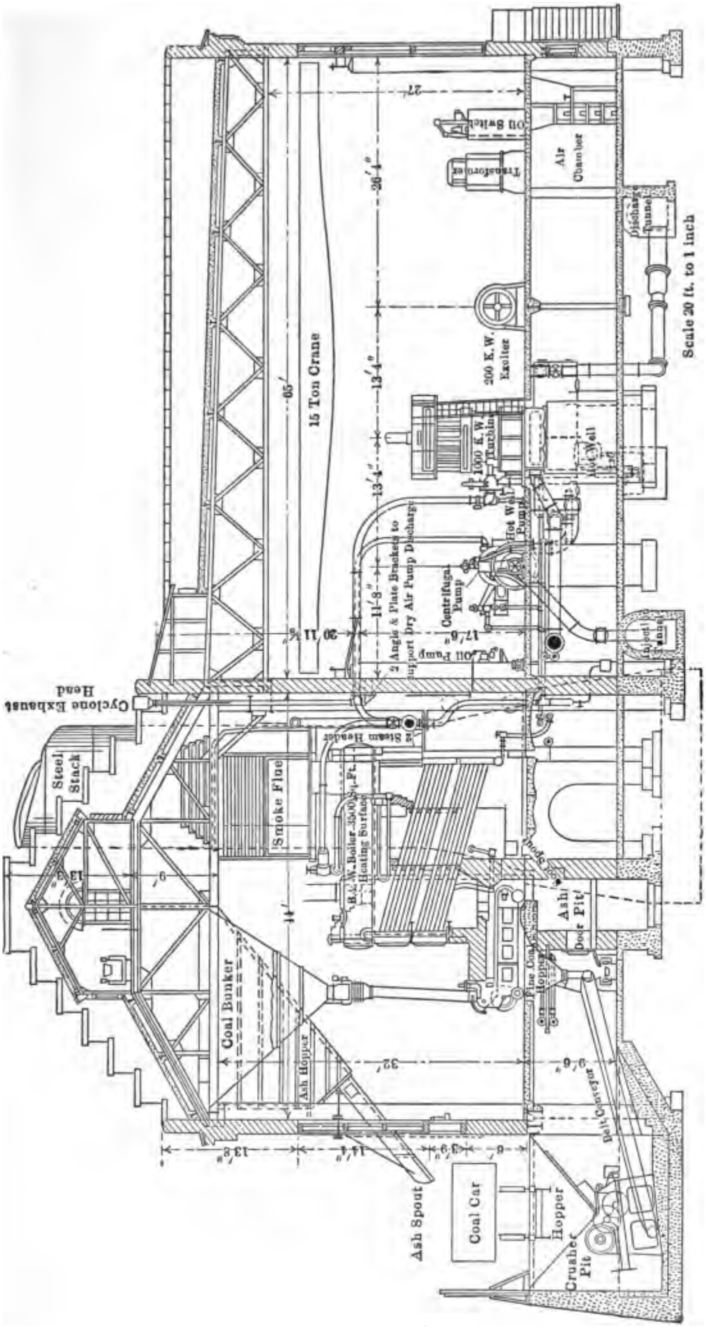

15 Ton Crane
Coal Bunker
Ash Hopper
Smoke Flue
Steel Stack
Cyclone Exhaust Head
Steam Header
B. & W. Boiler 3500 Sq. Ft. Heating Surface
2 Angle & Plate Brackets to support Dry Air Pump Discharge
Oil Pump
Centrifugal Pump
Hot Well Pump
Hot Well
1000 K.W. Turbine
200 K.W. Exciter
Transformer
Oil Switch
Air Chamber
Discharge Tunnel
Injection Tunnel
Ash Pit
Door
Fine Coal Hopper
Belt Conveyor
Ash Spout
Coal Car
Hopper
Crusher Pit
Scale 20 ft. to 1 inch

FIG. 61.

atures, and require the manufacturers to furnish a condenser sufficiently large to maintain the vacuum most economically.

Boilers.—Knowing the amount of water required per hour by the engines or turbines, the specified water rate of the auxiliary pumps may be added directly or in some cases the assumption may be made that the auxiliaries will take from 2.5 to 5 per cent. of the steam taken by the engines. A boiler h. p. is defined as "the evaporation of 34.5 lb. of water from and at 212° F. per hour." The boiler rating may now be determined from the equation

$$\text{Boiler h. p.} = \frac{W(Xr + q - q_o)}{34.5} \tag{99}$$

where

W = Steam consumption of engines and auxiliaries per hour in pounds.

X = Percentage of (W) which is dry steam.

r = Heat of vaporization of steam at absolute boiler pressure from steam tables.

q = Heat of liquid at boiler pressure from steam tables.

q_o = Heat of liquid at feed-water temperature from steam tables.

If proper consideration has been given to the overloads demanded at different times of day and during the various seasons of the year and provision made for a sufficient number of boilers being constantly out of service to guarantee plenty of time for cleaning, the capacity of the boiler plant may be based on the above equation, the size of the units being the next standard size above that given by the above equation. The largest capacity installed in a single unit is 500 h. p.

Boilers are broadly classified as water-tube and fire-tube, with a large number of varying designs under each classification. In spite of the fact that the water-tube boiler is the most expensive, it is rather generally installed in railway plants largely because of its ability to steam quickly under the sudden overloads that are experienced in railway practice.

Steam boilers require a special foundation with ash pits opening below the boiler room floor, usually into some type of ash conveying machinery. The boiler drums and tubes are freely sup-

ported from a steel frame in such a manner that they may readily expand with the rise in temperature. The setting, consisting of fire brick arches and walls surrounded by outside walls of common brick, completes the installation.

Boiler specifications should cover the following features:

Rating in boiler horse power.

Steam pressure.

Setting, single or in batteries.

Type of support, suspension or wall.

Size of steam and blow-off outlet and feed water inlet.

Grate area.

Safety-valve, gauges, and feed check valve.

Weight and size of breeching to stack.

Arrangement of arches.

Hydrostatic test.

Mechanical stokers for the automatic feeding of coal from the bunkers to the furnaces are generally installed in larger plants. They enable one fireman to care for several more boilers than with hand firing and reduce the temperature of the boiler room considerably.

Feed Water Heaters.—Reference to equation (99) will show that if the initial temperature of the feed water entering the boilers (q_o) be raised, the boiler horse power required for a given duty will be less. Add to this the lessened strain on boiler tubes and plates when warm water is fed to the boiler in place of cold and the further fact that this rise in temperature may be obtained by the use of heat in exhaust steam from auxiliaries or from the engine itself if operating non-condensing and the economy of installing a feed-water heater will be at once apparent. Such devices are therefore commonly installed in the boiler room and raise the temperature of the feed water to 200 or 212° F. before it enters the boiler. The feed-water heater may be either the open type operating at atmospheric pressure or the closed type in which the water is forced through the heater by the feed pump under boiler pressure. Provision is made in the heater for readily cleaning from same the scale often deposited by water containing mineral salts and in many installations the water-softening apparatus of the hot-water type is combined with the heater to

remove the scale forming chemicals and heat the water in one operation. Specifications need include only the boiler horse power supplied, the boiler pressure, the average normal feed-water temperature, and the approximate amount of exhaust steam available for heating purposes. If the apparatus is to include water-softening equipment, an analysis of the feed water or a sample of same must accompany the specifications.

Feed Pumps.—Steam driven reciprocating feed pumps of double the capacity necessary to furnish the boiler feed water maximum overload should be installed so that repairs may be made at any time without crippling the service. As the feed water supply is the back bone of the boiler plant its design should be carefully studied and generously provided for. The water should flow to the suction of the feed pumps by gravity if possible.

Draft.—Although mechanical draft of the forced or induced type is resorted to in some installations, the natural draft produced by chimneys is by far the most common. A single stack is usually sufficient for a medium size plant. If the use of inferior grades of coal is contemplated because of their low cost the draft provided must be correspondingly great. As the draft produced by a chimney is dependent upon its height, Mr. J. J. DeKinder advises that the following heights of chimneys be adopted for the various grades of coal.

TABLE XVI.

HEIGHTS OF CHIMNEYS FOR VARIOUS GRADES OF COAL.

Coal.	Height in feet.
Free burning bituminous coal	75
Slow burning bituminous slack	100
Slow burning bituminous coal	115
Anthracite pea coal	125
Anthracite buckwheat coal	150

As the formulæ used in chimney design involve the height and area and as the capacity in boiler horse power for which a chimney can supply draft is proportional to the latter factor, it

is well to assume the height first for the degree of draft required and the type of coal used and calculate the necessary area of cross section from formula (100). Occasionally the reverse process may be more desirable.

Kent's formula for chimney design which is commonly used is

$$E = \frac{\text{Boiler h. p.}}{3.33\sqrt{H}} \qquad (100)$$

where

E = Effective area of cross section.

H = Height in feet.

Chimneys of small dimensions are sometimes constructed of sheet iron but in larger designs are either common brick, Custodis radial brick, or concrete. Linings are provided generally for one-half or the entire height depending upon the temperature of the flue gases, but care must be taken to have the lining entirely independent of the outside walls to avoid troubles from expansion and contraction.

That the cost of chimneys is an item of some consequence in the first cost of the power plant, especially in the case of tall ornamental chimneys, will be noted from the costs and estimates which follow.

Coal and Ash Handling Machinery.—The judgment of the consulting engineer must be exercised in determining the extent to which coal and ashes shall be handled mechanically in a plant of given size. Where mechanical stokers are used, some type of coal and ash handling machinery is generally found, usually the continuous belt, bucket type of apparatus used for the two purposes of removing ashes from under the boilers to the outside of the station or to empty cars on the railway siding and also taking coal from the crushers and delivering it to the overhead bunkers. In some installations ash cars running longitudinally under the boiler room floor convey ashes from the boilers to an elevator shaft and thence outside the building, while the same cars and elevator are used for coal hoisting. This is cheaper in first cost but more expensive to operate than the former type. In large stations on the water front additional equipment is found for raising coal from the holds of coal barges to the crushing machines.

In any event the coal and ash handling machinery, commonly

electrically operated, is expensive in first cost. It reduces the operating charges, however, and it is therefore necessary to balance the fixed charges of its installation against the saving in operating cost, in order to determine whether or not its installation is warranted.

Arrangement of Equipment.—The most convenient arrangement of apparatus and wiring in a power station is greatly influenced by local conditions. A good idea of such arrangement may

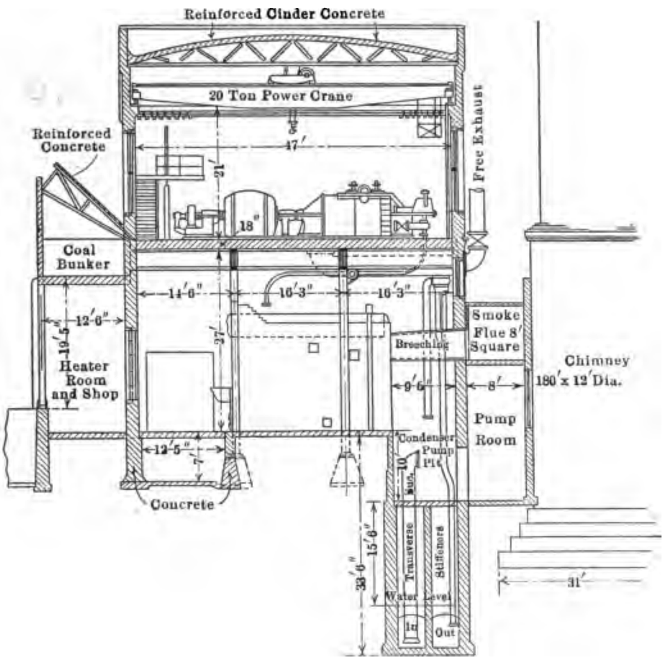


FIG. 62.

be obtained from Fig. 58 which represents a transverse section through the boiler and engine room of a typical power station using reciprocating engines direct connected to alternators, water-tube boilers, and jet condensers. A similar section through the high tension switch house is shown in Fig. 59. A plan view of a gas engine station will be found in Fig. 60, while Fig. 61 shows a section of the turbine station of the Indianapolis and Cincinnati Railway Company at Rushville, Indiana.

Cost of Power Station Equipped.—Complete power stations including buildings, but not cost of land, may be estimated to cost between $100 and $150 per kilowatt of rated output, depending upon the elaborateness of design and the addition of mechanical labor saving and safety devices. Occasionally the above minimum figure may be greatly reduced, as was the case of the rather unique double-decked station of the Fort Wayne and Northern Indiana Railway Company, Fig. 62, located in Fort Wayne, Indiana, whose detailed costs listed in Table XVII are taken from a paper before the American Street and Interurban Railway Association by Mr. J. R. Bibbins.

TABLE XVII.

COST OF COMPLETED POWER STATION. 8500 KW. NO SUBSTATION APPARATUS.

	Total cost.	Cost per kw.
Building: Including general concrete and steel work, galleries, coal bunker, smoke flue, condenser pit, coal-storage pit, etc.	$93,217	$10.97
Generating Plant: Including turbine, generators, exciters, cables, switch-board, transformers, and ventilating ducts.	259,711	30.55
Boiler Plant: Including boilers, superheaters, stokers, piping, pumps, heaters, settings, breechings, and tank.	118,313	13.92
Condenser Plant: Including condensers, pumps, free exhaust, water tunnels, and intake screen.	33,790	3.98
Coal Handling Plant: Including gantry crane, crusher, motors, and track.	7,990	0.94
Erection, superintendence, engineering, and miscellaneous.	50,500	5.94
	$563,520	$66.25

In contrast to the above double-decked station there may be found listed below the final estimate exclusive of land for a modern interurban power station in the south of 2000 kw. rated capacity involving substation equipment of 300 kw. capacity. This estimate is given in considerable detail as it is believed it will be of value in determining the relative costs of the

various portions of the equipment, even if the actual prices do vary, as they must from time to time. While the cost has been reduced to a kilowatt basis it should be stated that the estimates are from detailed figures based upon actual quotations, the values per kilowatt being results of the estimate and not the basis thereof.

ESTIMATE FOR COMPLETE INTERURBAN POWER STATION 2000 KW. RATING WITH 300 KW. SUBSTATION EQUIPMENT.

		Total cost	Cost per kw.
Surveying and clearing site	$300		
Excavating and Grading 10,000 yd. @ 25 cents	2500	2,800	1.40
Building proper, 12,000 sq. ft. @ $3.25	....	39,000	19.50
Machinery foundations, 2 turbine foundations, 100 yd. @ $10	1000		
1 Stack foundation, 200 yd. @ $8	1600		
2400 h. p. Boiler foundation, @ 1.60 h. p.	3850		
2400 h. p. Boiler settings @ 2.60 h. p.	6250		
Miscellaneous foundations, 100 yd. @ 10	1000	13,700	6.85
Stacks and Flues, 1 stack 9'x180' (Custodis)	8000		
2400 h. p. flues @ 1.00 h. p.	2400		
Dampers, Regulators, etc.	1000	11,400	5.70
Coal and ash handling apparatus, locomotive crane	9000		
Conveyor, crusher and scales	7500		
Ash cars and track	600		
Ash pit	500		
Storage yard tracks, etc.	1500		
Conveyor trestle	1000	20,100	10.05
Cranes, lighting, plumbing, etc., Crane	5000		
Lighting,	1500		
Plumbing	1000		
Gratings, railings, etc.	1000	8,500	4.25
Wells, intakes, etc.	....	20,000	10.00
Boilers, stokers, etc., boilers, 2400 h. p. @ 15.50 erected.	37200		
Stokers, 2400 h. p. @ 5.00 erected	12000	49,200	24.60
Piping, valves, etc.	....	23,000	11.50
Steam turbines, Curtiss turbines 2-1000 kw.	60000		
Frt. and starting	3000	63 000	31.50
Auxiliaries, Heater, 1800 h. p.	900		
Condensers, 2 @ $5,500	11000		
Feed pumps, 2 @ 1,100	2200		
Fire pump, 1 @ 1,100	1100		
Oiling system	1500		
Freight and erection	2000	18,700	9.35

ESTIMATE FOR COMPLETE INTERURBAN POWER STATION 2000 KW. RATING WITH 300 KW. SUBSTATION EQUIPMENT.—*Continued.*

		Total cost	Cost per kw.
Generators, exciters, rotaries, etc., Rotary converter, 300 kw. @ $16.00	4800		
Transformers, 480 kw. @ 10.00	4800		
Turbine exciters, 2–35 kw	3600		
Motor-generator set, Ltg. 100 kw. @ 40.00	4000		
Frt. and erection	2000	19,200	9.60
Switchboards and wiring, 16 panels	7900		
3 blank panels	150		
Miscellaneous brackets, etc	150		
Frt. and erection	1000		
Wiring @ $1.50 per kw	3000		
Switch cells	1000	13,200	6.60
Miscellaneous	....	2,500	1.25
Sundry supplies and expenses	....	2.500	1.25
Grand total exclusive of land and engineering salaries and commissions.	....	$304,300	$152.00

CHAPTER VI.

BONDS AND BONDING.

The circuit which supplies current from the substation to the car has already been outlined. The return portion of this circuit is made up of the track rails, being augmented by return copper feeders in parallel with the track only incases of heaviest service. As rail lengths of either 30 or 60 ft. are used a single rail will have 88 or 176 points per mile at which the electrical resistance of the connection between rails made by means of corroded fish plates would normally be very high. With this high resistance directly in series with the return circuit, any reasonable addition to the copper in the positive feeders is of little value. It was quickly found, therefore, in the operation of the early railway systems that the ends of rails must be connected electrically by conductors of lower resistance than the fish plates. These conductors have been designated as "bonds."

In the first installations bare copper negative return wires were laid along the ties between the rails and connected with the center of each length of rail with a copper wire. This method, however, proved very expensive and was abandoned, although it has been reinstated recently of necessity in similar form where traffic is very heavy, particularly in city systems. Later the ends of rails were bonded by means of No. 6 galvanized wire bonds clamped under the heads of track bolts. Such bonds were not only soon destroyed by galvanic action in the earth but were found to be of such high resistance as to be of little use. A slight decrease in the contact resistance of these bonds was later affected by forcing the bond wires into holes drilled in the heads of the bolts. The inability to reduce the track resistance sufficiently by any of the above means led to the introduction of the solid copper bond which in turn developed into the laminated strip copper and stranded copper bonds which are preferable because of their flexibility.

Several distinctive types of the latter bonds have now come into

very general use and a brief description of each will therefore be found below.

Compressed Terminal Bonds.—This type of terminal has been applied to various designs of copper bonds. It consists of a cylindrical head varying from 5/8 in. to 1 in. in diameter and slightly longer than the thickness of the web of the rail. This head is forced into a recently reamed hole in the web of the rail by means of a heavy screw clamp provided with a conical contact which engages the center of the bond head and causes it to expand and flow under the pressure applied so that it makes intimate contact with the inner surface of the hole and heads over, rivet like, so as to prevent easy loosening or removal. Some compressed terminal bonds have their heads drilled with an axial hole through which a tapered steel pin in driven in order to expand the copper head well into the hole in the web.

Compressed terminal bonds may be installed so as to surround the fish plate or they may be of the "protected" type, installed before the fish plates are put on and later covered by the latter plates, thus protecting the bond from mechanical injury or theft. When installing this bond great care must be exercised not to drill the holes much before the bonds are inserted and to use a lubricant when drilling holes which will not produce an insulating film on the inside surface of the hole. Clear water or a solution of bicarbonate of soda and water may be used but oil and soapy water should not be tolerated as lubricants.

Soldered or Brazed Bonds.—Bonds similar to the above but with flat tinned heads are sometimes soldered or brazed to the side of the rail head or under the rail flange by means of a gasoline or oxy-hydrogen blow-torch after the rail has been brightened at the point of contact. These bonds have not proved entirely satisfactory, however, as they are quite likely to work loose and are also quite easily stolen.

Electrically Welded Bonds.—A process of electrically welding a short laminated copper bond, provided with a brass head, upon the sides of the rail heads has recently been developed. This is accomplished by the use of a very large alternating current passing through the very small areas of bond, rail head, and carbon terminal in series and thus bringing the two metals to a welding heat.

While this process is termed welding it is more correctly brazing, since two different metals are joined with a flux of borax between. The large alternating current necessary is produced by making the yoke and jaws which grip the bond and rail head a part of the secondary circuit of a current transformer whose primary is supplied from the alternating current side of an inverted synchronous converter. This converter is mounted on the car which carries the bonding outfit and is supplied with direct current

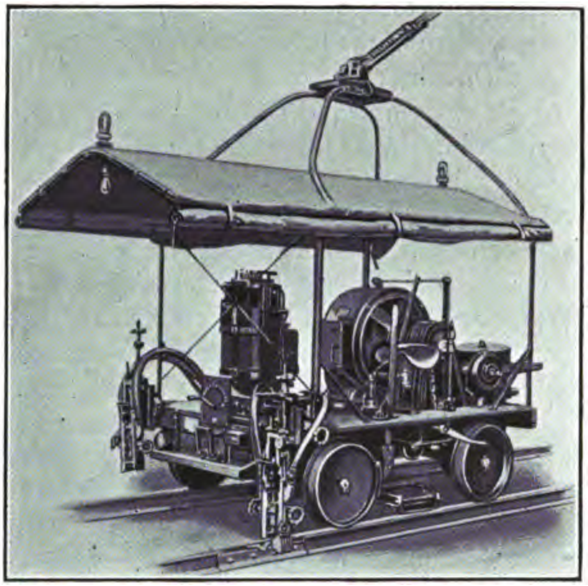


FIG. 63.

from the trolley. The ratio of transformation and impednace of the transformer secondary circuit are such that the current flowing through the weld is in the neighborhood of 1000 amperes. The particular equipment from which these values were obtained, Fig. 63, involves a 15 kw. transformer supplied from and 18 kw. inverted synchronous converter operating at a frequency of 25 cycles. The transformer was connected for two voltages of 375 and 500 volts respectively, while the secondary voltage varied from one to seven volts. The converter was also used as a motor to propel the car.

In this particular test[1] with the 500 volt connection, the time required to make a weld averaged 82 sec. with an input to the car per bond of 797 watt hours. An estimate of the cost of electric welding, assuming that 40 welds per day can be made would, therefore, result as follows, if power costs 2.5 cents per kilowatt hour at the car.

Cost of energy 0.797x.025	$.019
Cost of bond	.30
Cost of labor	.112
Sundries	.01
	$.441

This estimate is slightly low since it is always necessary to grind a bright place on the head of the rail before the bond is applied. This is accomplished by means of an electric motor-driven grinder connected with the trolley. The power for this purpose was not included in the above estimate, although a labor item was allowed to cover the work. It is safe to say, however, that these bonds may be installed for 45 cents each while the other types vary from something less than this up to 70 cents, each installed.

Amalgam Bonds.—Bonds consisting of semiplastic amalgam forced between the brightened surfaces of rail web and fish plate are occasionally found, although not in common use.

Aside from the above, several methods of making continuous rail joints of high electrical conductivity may well be classified under the heading of bonds. Such methods in common use are as follows:

Cast Welded Joint.—In making this joint, melted iron of special composition and high conductivity is poured around the rail ends, with the exception of the heads, while they are enclosed in a sand or iron mould of such shape as to leave a heavy lug of cast iron about the ends of the rail. While it is rather difficult with this process to raise the temperature of the rail quickly enough to insure molecular adhesion between the rail and the molten metal, yet very satisfactory results have been obtained in many instances from both the standpoints of electrical conductivity and mechanical rigidity.

[1] Thesis, Purdue University, 1910, by Broadwell, Cole, and Stevenson.

Thermit Welded Joint.—A combined joint and bond of comparatively recent origin is produced by the "thermit" process. As in the previous method a mould of sand is made about the rail ends but in this case only sufficient thermit for one joint is melted at a time. This melting is accomplished by making use of the well known fact that finely divided aluminum when oxydized develops a great amount of heat. This reaction has been recently brought under control so that a small amount of powdered aluminum mixed with iron oxide, if ignited with a small amount of ignition mixture, will react as above explained with sufficient heat to melt the iron which in turn is poured about the rail ends. This produces a joint similar to the cast weld with less metal but with apparently quite as good electrical and mechanical characteristics.

Electric Welded Joint.—In contrast to the electric welded bond mentioned above there may be found in the city tracks of many railway companies the electric welded rail joint. This, a rigid rail joint, produced by electrically welding heavy iron bars on either side of the webs of adjacent rail ends, should be carefully differentiated from the electric welded bond, although the process of welding is almost identical with that outlined above, with the exception that iron only is used and the size of weld and corresponding power used are much greater. In this latter type of joint iron filler blocks are inserted between the rail ends and ground to the form of the rail head so that the joint is entirely closed and the operation of cars over rail joints is made so much the smoother. This joint has given very satisfactory service both electrically as a bond, for its conductivity is practically equal to that of the rail, and mechanically as a rail joint, the breakages not exceeding 1 per cent. of the total joints welded after several years of service in at least one installation and averaging very close to this record on several other roads.

When considering any of these three methods of making combination rail joints and bonds where the joint is necessarily mechanically rigid, it should be borne in mind that the track will expand in hot weather sufficiently to throw it noticeably out of gauge if it is not rigidly held in place by street paving. None of these methods are therefore suitable for anything but paved city streets, unless an exception be made of the few cases where they have

been tried with expansion joints every few hundred feet. At these joints of course some other type of bond must necessarily be installed.

As these processes combine a rail joint with a bond, doing away with fish plates, track bolts, and other types of bonds, their expense is naturally much greater than that of any other bond alone. [1]Herrick and Boynton give average prices for these combined

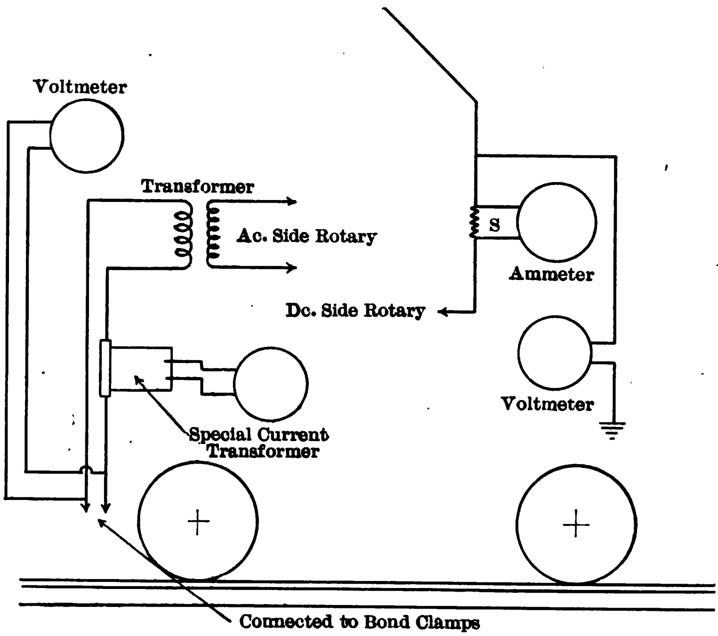


FIG. 64.—Connections for electric welding of bonds.

joints of from \$2.67 each for cast welded joints and \$4.50 each for the "Thermit" process, up to \$5.50 or \$6.00 per joint for the electric weld. These figures do not include opening and closing the pavement around the joint in case old track is being treated, which cost will vary from \$1.00 to \$1.25 per joint.

Bond Testing.—The bond resistance of a well bonded track using 4/0 B & S bonds will range from 5 to 7 per cent. of the resistance of the track return. With a few missing bonds or with poor contacts between bonds and rails this resistance may

[1] American Electric Railway Practice, by Herrick and Boynton.

be increased many times. While the maximum allowable voltage drop in the return circuit is often very rigidly fixed in the city systems by municipal ordinance, it is for the interest of the operating company to keep this resistance at a minmium value, since the voltage at the car varies inversely and the losses vary directly with the resistance. It has been customary, therefore, to make frequent tests of the resistance of rail bonds and the standard has been rather arbitrarily set that the resistance of a bond shall be less than that of 3 ft. of rail.

The comparison of the resistance of the bond with that of 3 ft. rail may be very readily made by making use of the current

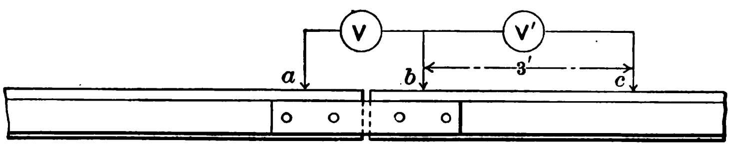


FIG. 65.—Connections of bond testing meters.

flowing in the rail. Two contacts, (a) and (b) Fig. 65, consisting of hardened steel knife edges or points connected to a milli-voltmeter (V) are applied to the head of the rail at a distance apart corresponding to the length of the bond. A third contact (c) is permanently spaced 3 ft. distant from one of the former contacts, (b). If another milli-voltmeter (V′) be connected between (b) and (c) and read simultaneously with the meter connected to (a) and (b) the readings are proportional to the resistance of a 3-ft. section of rail and that of the bond respectively. The bond may be pronounced in satisfactory condition if

$$V < V' \tag{101}$$

while if (V) be too great its departure from the required value may be recorded as

$$\frac{100(V-V')}{V'} \text{ per cent.} \tag{102}$$

Care must be exercised in making these tests not to damage the milli-voltmeter by attempting to measure an open bond. It is always well to try the bond on a meter with a 15 volt scale first and if the drop in potential is found to be within the range

of the milli-voltmeter to make the final reading with the latter instrument.

As this process is a rather slow and tedious one where there are a large number of bonds to be tested, various methods have been devised for making the tests on a car as the latter is traveling over the road. Usually this is necessarily done when the regular cars are off the line at night or with very little varying current in the rails. The current sufficient to determine the voltage drop in rail sections and bonds is fed through the local rail section by means of specially designed trucks, the current being controlled by a rheostat on the test car.[1]

If it be desired to learn only the total resistance of the track return this may be determined after the cars are off a section of line by passing a measured current through the rails by means of a feeder to the distant end of the line and a rheostat at that point in series therewith. A second feeder may be disconnected from the generator temporarily and used as a potential lead so that the fall in potential in the track may be read upon a voltmeter in the power house.

Cross Bonding.—Thus far the bonding of rail ends alone has been considered. It is sometimes necessary to provide against the greatly increased resistance of the return circuit due to a possible open bond by connecting the rails together electrically by means of cross bonds spaced several hundred feet apart. These usually consist of bare copper wire of approximately the size of the bonds soldered to the bonds on opposite rails or to special single headed bond terminals forced into the rail web. Thus if a bond be open, the return current on that particular rail would follow the nearest cross bond to the other rail and find its way back to the original rail at the next cross bond nearest the power station.

As the bonding of all joints in special track work such as switches, cross-overs, and frogs would often involve a large number of bonds, a heavy cable is often laid around such portions of the track and thoroughly bonded to the sections of track on either side thereof.

[1] Practical Electric Railway Handbook by Herrick.

CHAPTER VII.

Electrolysis.

The subject of the electrolysis of underground pipe systems is so closely allied to that of bonding that no sharply defined line can be drawn between them. Beginning with the rather general introduction of the direct current street railway systems in the early nineties, with their track return and relatively poor bonding, and extending through the rapid development and improvement of such systems, the question of electrolysis, its cause and prevention, has maintained an important although ever decreasing prominence in the studies and discussions of the engineers of gas and water works corporations as well as the telephone and street railway interests.

It has, of course, been known for a long time that if a direct current be allowed to flow from a metal electrode, through an electrolyte to a second metal electrode, a chemical reaction takes place at the expense of the positive plate, *i.e.*, this plate is actually eaten away, the metal removed therefrom forming a salt with some of the acid radicals of the electrolyte. During these reactions which take place similarly when moist earth is the electrolyte it was noticed that hydrogen was given off at the cathode or negative terminal while oxygen was liberated at the anode. It was supposed for some time that those free gases were formed from the decomposition of the water in the earth. When it was later found, however, that this action often took place with potentials between terminals of the order of hundredths and even thousandths of a volt, which are not sufficient to decompose water and free these gases at their respective electrodes, a further study of the problem was undertaken.

Experiments carried on at the University of Wisconsin and recorded in the discussion of a very able paper upon this subject presented before the American Institute of Electrical Engineers by the late Isaiah H. Farnham in 1894 demonstrated the fact that

with iron electrodes embedded in moist earth electrochemical action is substantially as follows: Most earths contain salts of alkaline metals. Merely a directive electromotive force of the order of .001 volt will cause the acid radical of these salts to be isolated. This radical then attacks the anode. Suppose sodium sulphate ($NaSO_4$) be present in the earth; this is broken up by the current into (Na) and (SO_4). The SO_4 forms with the positive iron electrode ($FeSO_4$) while the hydroxide of sodium($NaOH$) is formed at the cathode. When the earth in the neighborhood of the terminals becomes saturated with these compounds they diffuse toward one another and finally meet in the earth at a point easily detected by the formation of a green precipitate of ferrous hydroxide and the original salt. This reaction causes a local rise in temperature at the point where the precipitate forms. The reactions mentioned above, which take place at the electrodes, release oxygen gas at the anode and hydrogen at the cathode, the former resulting from an excess of SO_4 forming an acid with the hydrogen of the water and setting oxygen free. The latter is the result of the formation of the hydroxide of sodium with water; the free atom of hydrogen from the water being liberated.

The one point of practical interest in this series of reactions is the fact that iron is removed from the positive electrode to make ferrous sulphate and later ferrous hydroxide, and the size and weight of this plate are reduced thereby. This loss of metal from the buried plate is proportional to the current flowing therefrom. Now if the track return circuit be of high resistance, a portion of the return current will flow back to the power station on underground pipes and cable sheaths, leaving these conductors at points near the power station to complete the circuit through the earth or on the rails and negative cables to the switchboard.

Since the above chemical reactions take place in the case of electric railway currents leaving water and gas mains and the sheaths of telephone cables and entering the earth with values ranging from an infinitesimal leakage up to several hundred amperes in extreme cases, the importance of the study of the magnitude of troubles from electrolysis and the remedies to be applied is at once apparent.

In the early days of electric traction the bonding of the track

and the proper installation of a low-resistance return circuit were seriously neglected as has been explained in the previous chapter. It was also customary at first to connect the negative terminal of the generator with the trolley and the positive to the rail in

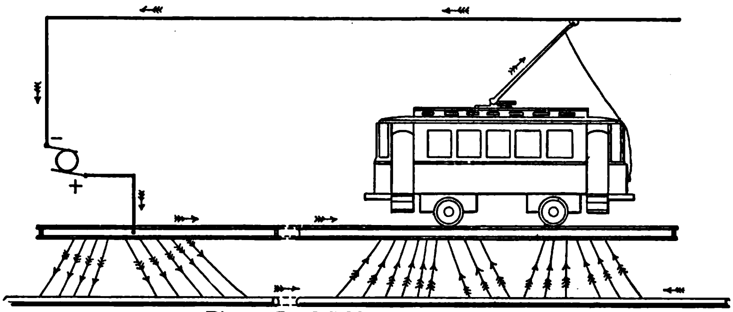


FIG. 66.—Direction of current with negative trolley.

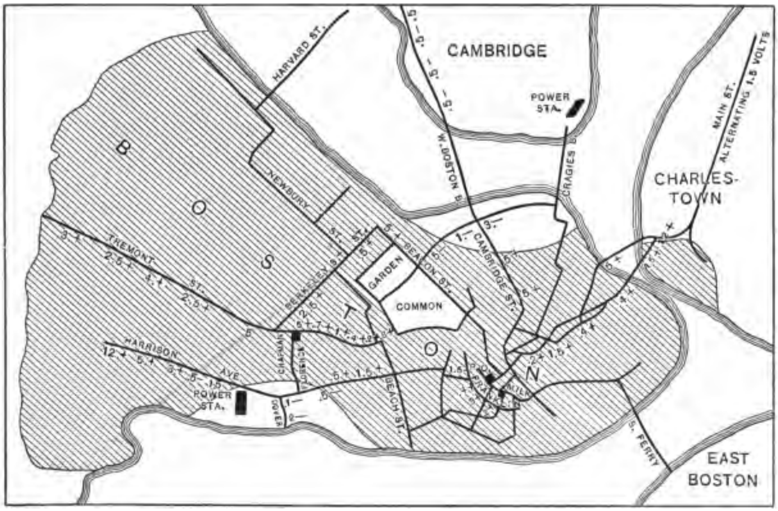


FIG. 67.

many installations, this being just the reverse of the present method. These two conditions tended, first, to force a relatively large proportion of the current to follow the pipe and cable systems in place of the track and, secondly, to make such pipe and cable systems positive to the rail over a wide area of territory in the average city.

This condition is clearly shown in the accompanying Fig. 66, which shows the direction of earth currents, and Fig. 67, representing the conditions in Boston, Mass. when the question of danger from electrolysis was first seriously considered. At the time this map was plotted from a large number of tests made of the voltage between pipe systems and rails, the trolley was negative and the rails positive. The shaded area designated as the "danger area" represents the territory in which the pipe systems are positive to the rails and therefore in which electrolysis might be expected to take place. The large extent of this danger area implies a great amount of possible trouble from electrolysis and a considerable expenditure of time and money for the proper maintenance of tests and the location of serious leakages of current.

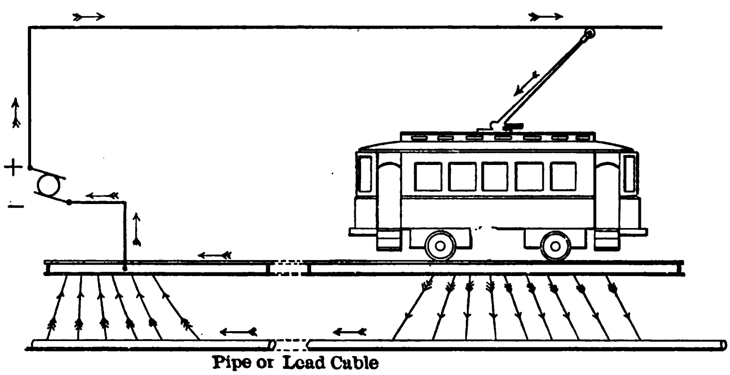


FIG. 68.—Direction of current with positive trolley.

A marked advance was soon made, however, in this problem when the trolley was connected with the positive terminal of the generator and the rails with the negative terminal as in Fig. 68. This change would naturally limit the danger zone to a comparatively small area near the power station where the current which returned on the various pipe lines would leave these conductors and pass through the earth to the rails or return conductors and thence to the negative terminal of the generator. The effect of such a reversal of trolley polarity is obvious in Fig. 69 which represents a potential map of the territory included in Fig. 67 taken after the trolley of the West End system of Boston was made positive. This limitation of the area in which electrolysis

may take place would usually increase the current leaving the pipes at any one place. To prevent serious trouble from electrolysis at those points it is customary to connect the pipes with the rails or return negative feeders by means of heavy copper cables. In fact this practice is often employed at other points along the line where pipes are found to be positive to the rail. This, policy, however, unless carefully carried out, often increases the electrolytic effects from any pipes which happen to

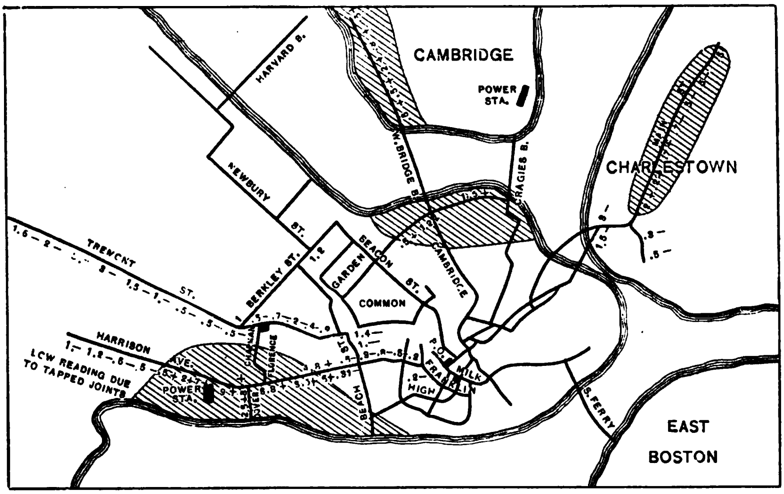


FIG. 69.

be left unconnected with the rails because of the greater area exposed by negatively connected pipes and therefore the presence of lower resistance paths through the earth. Such a condition is well illustrated by Fig. 70.

In this connection it might be of interest to note some of the results of electrolysis with currents of different magnitudes. Experiments have proved that one ampere flowing steadily from an iron surface will remove approximately 20 lb. of iron in one year, while the same current flowing continuously from a lead cable sheath or pipe will eat away 75 lbs. of lead in the same time. A 48 in. iron water main in Boston was pitted in various places to a depth of 9/16 in. in from four to five years, the average potential between pipe and rails being 8 volts with a current

flowing in the pipe ranging from 5 to 95 amperes. In this case the pipe was about 2 1/2 ft. below the rails of the street railway company.

Nor is the trouble confined alone to the points where the current leaves the pipe for other conductors. The joints in pipe lines often have relatively high resistance as compared with the pipe itself and even when compared with the surrounding earth in some instances. This is particularly true of the so-called bell and spigot pipe which is so commonly used for large water mains. At these high resistance joints the current or a portion thereof passes in a shunt path through the earth around the joint. This

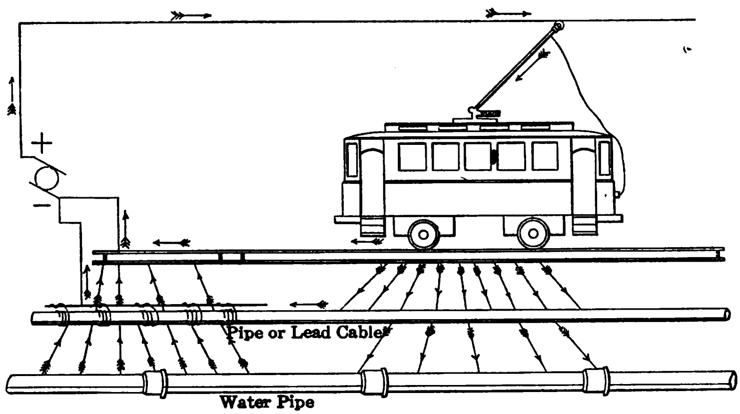


FIG. 70.—Current with portion of pipe system bonded to rail.

causes an eating away of the iron on one side of the joint only, if the current flow is always in one direction. This effect at the joint is, of course, increased when the pipes are connected with the power station by means of copper conductors for the reason that such connection tends to increase the flow of current in the pipe line. Because of the increase of electrolysis at the joints and the impracticability of bonding these joints, many engineers are opposed to this method of decreasing electrolysis.

Aside from the above mentioned methods of electrolysis reduction, two other plans have been proposed, although neither has been adopted to any extent. Both of these proposed plans involve the use of the double overhead trolley. In one case the

second trolley takes the place of the rail return, the rest of the system remaining unchanged, while in the other plan the rail becomes the neutral of the familiar three-wire system. In the latter case a potential of approximately 1200 volts is maintained between the two overhead trolley wires while half this voltage is impressed between either trolley and the rail. Obviously only the current due to unbalanced load on the two sides of the three-wire system would return to the power station on the rails and, as this would be a very small portion of the total in a well planned system, the trouble from electrolysis would be reduced considerably. With the 600 volt two-wire system, however, no connection is made between rails and power station and although there may be local currents in the rails and earth in some instances, these earth currents and the electrolysis resulting therefrom are reduced to a minimum.

The principal objections to these two systems which have probably prevented their general introduction may be listed as follows:

High first cost.

High maintenance cost.

Difficulties in insulation.

Complication at crossings.

Greater overhead obstruction of streets.

It is believed that the above difficulties are self-explanatory in a system of this type, involving as it does the support of two heavy bare conductors at a distance of from 15 to 20 ft. above the street, separated from each other by a distance of from 12 to 18 in. and maintained at a potential difference of either 600 or 1200 volts. No further description of such installations will therefore be given. Suffice it to say, however, that although the advantages of this system from the standpoint of electrolysis prevention were set forth in the very infancy of electric traction, there are not more than three or four such systems in operation in the United States today. Conspicuous among these systems have been the installations at Cincinnati, Ohio, and Key West, Florida.

Some municipalities attempt to insure themselves against troubles from electrolysis by requiring that the fall of potential on all track return circuits be within a certain predetermined limit. For

example, in rehabilitating the electric railway systems in Chicago recently a maximum possible rail drop of 25 volts was specified by the city. In order to avoid exceeding this limit with maximum traffic, negative return feeders were necessary and as the distribution system was largely underground, provision was made for these negative cables in the conduit lines. Fig. 71 illustrates the standard track construction adopted involving the use of frequent cross bonds connected to the longitudinal negative return cables.

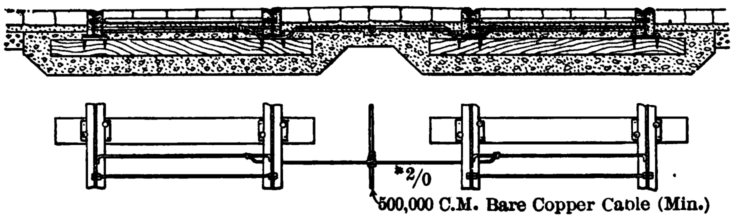


FIG. 71.—Standard cross section of track construction in Chicago.

The above regulation is a step in the right direction, for it seeks to remove the cause of the trouble, *i.e.*, eliminate stray currents, rather than so direct the existing stray currents that they may do no harm. If stray currents are to be prevented or at least reduced to a minimum, it is necessary to reduce the resistance of the return circuit as low as possible. Another method which accomplishes this same end more completely is the use of a negative booster connected in series with the return circuit or often connected to a single point in the return circuit and therefore lowering the potential of that point to such a negative value that the current will not leave the rail. In order to do this it is only necessary to supply a low voltage heavy current generator driven by a motor in the substation with its negative terminal connected to the return circuit at the point of greatest leakage. This method may be likened to the formation of a vacuum on a pipe line at some particular point in order to draw the contents of the pipe system to that point because of its low absolute pressure.

Early in this chapter the statement was made that the question of electrolysis has been given decreasing publicity by the water and gas companies since the difficulties in connection therewith were first made manifest in the early nineties. This has taken place in

spite of the fact that no complete cure has been found for the difficulty. This apparently paradoxical condition has come about largely because of the increased activity on the part of the railway managements to better inspect and maintain the track. The value of a low resistance return circuit is now well known among electric railway men and by frequent testing, by replacing and increasing the capacity and efficiency of bonds, and by the installation of cross bonds and negative return conductors, the track circuit has been placed in a condition to return practically all the current to the power station so that the leakage by way of shunt paths through the earth and its pipe systems has been reduced to a minimum.

In testing for electrolysis troubles, methods similar to those outlined in the previous chapter are adopted. As dangerous electrolysis occurs only at points where the pipes are positive to the rails, such points are readily determined by connecting a milli-voltmeter between the rails and convenient points, such as hydrants on the pipe lines. The positive pipes are then permanently connected to the rails by means of a copper bond. To determine the actual current flowing in the pipes it is only necessary to find the fall in potential between two convenient points on the pipes at a known distance apart. The resistance of the pipe can usually be found from tables or it may be found by test. The current is then calculated from Ohm's law. That such leakage currents are produced by the railway system and that they vary with the load on the railway system is well demonstrated by the tests plotted in Fig. 72 which represent readings of current flowing in a 36-in. water main compared with the power station log of current output during the same period of time. The similarity of the two curves plotted with the same abscissæ of time is rather surprising.

In the case of electrolysis, therefore, as well as in many other difficulties which engineers encounter from time to time, it may be said that at the time the effects of this action were first discovered in Boston the problem looked most serious for electric railways throughout the country and many suits were brought by water, gas, and telephone companies against the railway companies for damage to pipe lines, etc., the test case at Peoria, Illinois, which

railway men have been following most closely, being still undecided after years of controversy. The problem has been studied carefully, however, and such means of reducing its serious effects

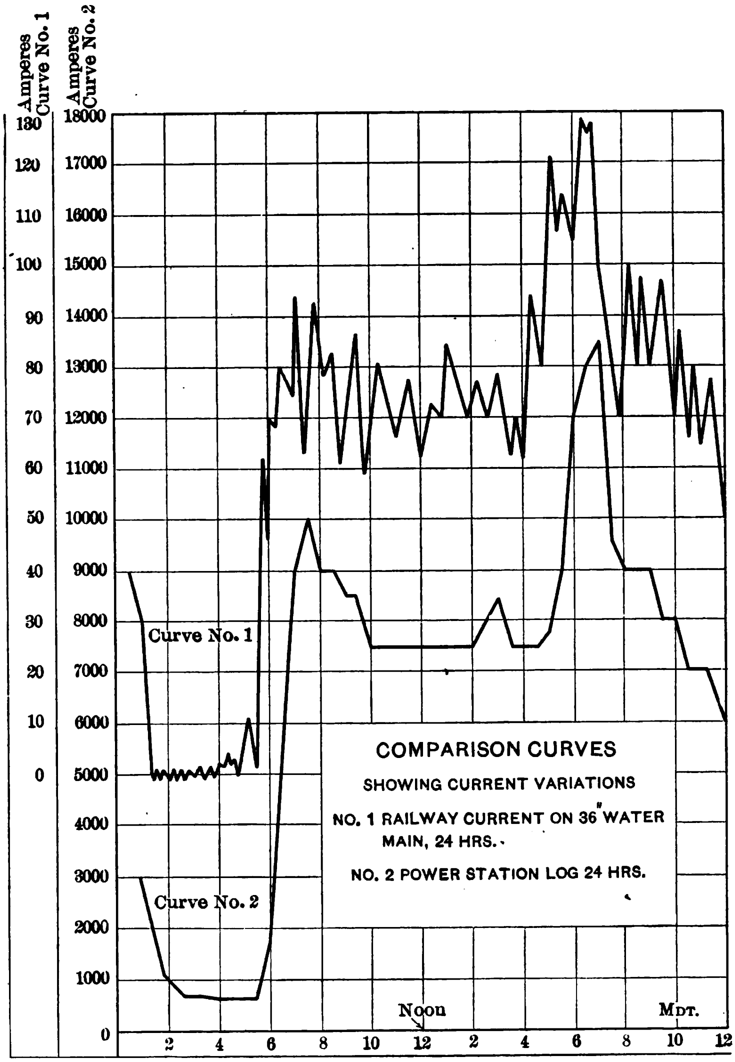


FIG. 72.

devised that while it can never be entirely eliminated, it may be said that its results are no longer serious, if careful and persistent testing and bonding be the policy of the railway company.

CHAPTER VIII.

SIGNAL AND DISPATCHING SYSTEMS.

The problem of dispatching cars and of protecting one car from another on the same section of track is largely confined to interurban systems, for in the case of city railways, speeds are low, the headway is small, and double tracks are commonly in use. Cars are therefore usually operated as closely as possible on a predetermined schedule by the car crews and considerable responsibility is placed upon them for the regaining of schedule time in case of delay. In many cities branch line dispatching is done by a starter stationed in the city square or at the junction point of branch line and the main tracks. For the above reasons, therefore, this chapter will be principally devoted to interurban systems, although the possible application of a number of the signal systems to urban car operation will be obvious.

A complete system of train dispatching by a single dispatcher for the entire road does away to a large extent with the necessity of signals other than those under the control of the dispatcher installed for the purpose of attracting the attention of a train crew for special orders while enroute, or to stop a car in case of an error in orders discovered after the last communication with the crew. Most of the signal systems are therefore operated in conjunction with a dispatching system and act as a check thereupon. Some of the more complete systems, however, are operated with little attention from the dispatcher and the complete automatic block signal system on a double track road may be practically independent of dispatcher's orders.

Where a dispatching system is adopted, those signals commonly used in steam railroad practice are occasionally found on electric lines, involving the manually operated signals and telegraphic train orders to way station agents. Even the "staff" system which is used extensively in England may occasionally be found. This is really a combined signal and dispatching system consisting

of two electrically interconnected mechanisms, one at either end of a block, which permit a staff to be removed therefrom if there be no train in the block ahead. A second staff cannot be removed from either of the terminal stations until the missing staff has been replaced at the farther end of the line. This system not only protects the block but also gives the train crew tangible evidence that they have the right of way in the block.

The dispatching system most common to electric railways is that using the telephone for communication between dispatcher and train crew. Telephone booths are either provided at sidings or a portable telephone is carried on each car which may be readily connected with the telephone circuit paralleling the track by means of a flexible cable and two-pole plug switch. It is customary to require the motorman to receive the orders and write same on an order blank which furnishes a carbon copy for the conductor. The order is checked by the conductor reading from the carbon copy to the dispatcher over the telephone. This check message is either ok'd or corrected by the dispatcher. Whereas there are many modifications of this method in use, the telephone is very generally adopted and has proved very satisfactory. In fact several of the steam railroad trunk lines have adopted the telephone in place of the telegraph for train dispatching.

Such telephone lines should be constructed for dispatching only, the business to be transacted between other officials or departments of the road being provided for by another line. This duplicate line is fully warranted in the interests of safety and the avoidance of train delays. Care should be taken also to insist upon the repeating of orders, for serious wrecks have occurred due to the train crew receiving but a portion of the order or mistaking an order given to a crew at the dispatcher's office with the receiver off the hook for an order intended for them. Repeating an order will correct these errors.

Aside from the telephone order and the possible stop signals, mentioned above, which may be under the control of the dispatcher, some railway companies provide a means at the disposal of the dispatcher for shutting off power from any desired section of trolley in order to prevent a wreck in case of emergency. Still

other officials believe this to be a dangerous tool in the hands of the dispatcher upon which he may tend to rely too frequently. Such a device applied to the feeder circuit breakers on the power station switchboard is illustrated in Fig. 73. In this case the tripping device is operated by a relay which is supplied with current from the trolley with a number of incandescent lamps in series and with the controlling switch in the dispatcher's office. This particular device is used by the Indianapolis and Louisville Traction Company. In making use of this device it should be remembered that it does not necessarily enable the car to be

FIG. 73.

stopped at once, for in the case of high-speed interurban roads the cars may travel for considerable distances at high speeds without the use of power. When the lighting circuit is not in use there is no indication to the car crew that the power has been shut off.

Signal Systems.—Returning to the signal systems which usually augment but may replace the dispatching system, it may be said that the present systems have been a gradual growth from the single incandescent five lamp series circuit between trolley and ground to the more elaborate automatic block signals similar to those used on steam roads which are now being rapidly adopted by the large interurban railroads.

For protection against accidents and in order that the schedule may be maintained, it is desirable that the train crew should know upon entering a block or certain section of the road

1. Whether there is another car in the block.
2. How many cars there are in the block.
3. What direction the cars are going.

The latter requirement is, of course, applicable to single track roads only. As a matter of fact, nearly all signals are confined to the first case only or the first and third classes, but very few in

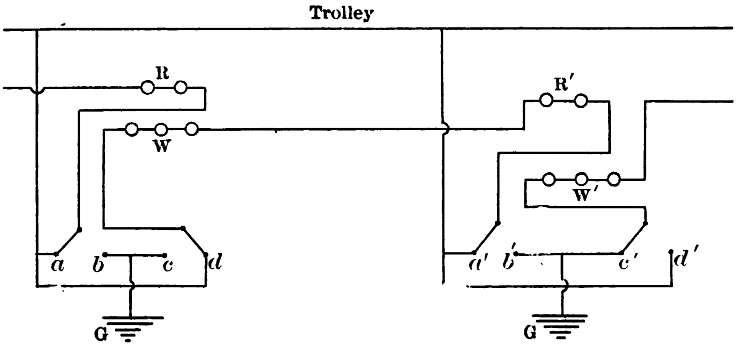


FIG. 74.—Simple lamp signal.

general use answer the second question. In order to do this automatically the circuits have become too complex, involving difficulties and excessive expense in their maintenance. Signals displayed on the cars are used to signify that another car is following in the same block.

Probably the most simple arrangement used as a signal, and one to which several roads have returned after trying out the more nearly automatic types, is that shown in Fig. 74. This consists of a series of five incandescent lamps connected as shown by means of a double-throw switch between trolley and ground, two of each group being located at one end of the block and three at the other. The group of three lamps is placed behind a white or green lens and the two lamp group provided with a red lens. Upon enter ing the block the circuit is closed by means of the switch which lights a red light at the opposite end and a white or green light at the entering end. Upon arrival at the other end of the block the lights may be switched out and the circuits are such that the lights

may then be lighted from either end. An extra circuit duplicating that of Fig. 74 should be provided, however, for operation in both directions. The advantages of this signal are its simplicity and the necessity of one of the crew leaving the car, when stopped, to operate the signal switch. Its disadvantages are that the signal light may be extinguished and the signal reversed from either end with a car still in the block and if the switch be accidentally left in the off position the signal cannot be operated from the other end.

Elaborating upon this principle and adding the automatic feature, the United States Signal Company has developed a signal

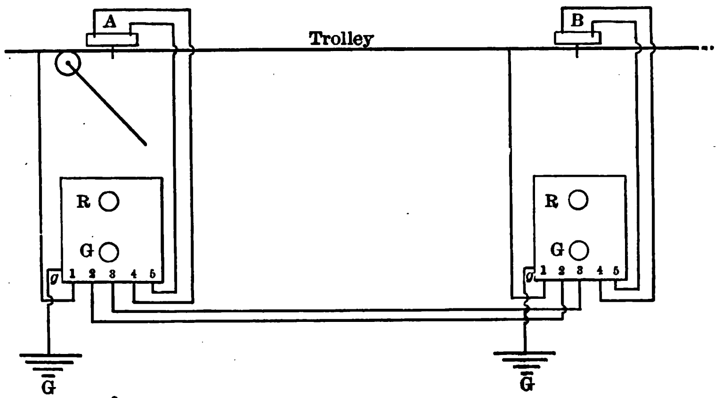


FIG. 75.—United States signal.

for single track blocks which has been adopted by many roads. It operates from the trolley circuit and consists of one signal box and trolley switch at either end of the block connected as in Fig. 75 and requiring two wires throughout the length of the block. A car entering the block at (A) makes a momentary connection between the trolley wire and wire No. 4, as the trolley wheel operates the iron tongue switch mounted on the trolley wire. This momentary connection closing a circuit to ground through a relay and a suitable resistance, completes the permanent circuit connecting the trolley wire through No. 1, the green lamp at (A), the signal line wire, the red lamp at (B), through resistance in box (B) to ground. Other cars entering at (A) do not change the signal setting, but a car leaving the block at (B) energizes wire No. 5 through the agency of the overhead trolley switch and trips the relay which

extinguishes the red light. A car entering at (B) performs the reverse operation, lighting the green light at (B) and the red signal at (A). The boxes and switches are therefore interchangeable. Red and green disks are displayed in some types of this signal for day use, although the lights are commonly used as day signals as well. This type of signal has given a fair degree of satisfaction although its maintenance expense is high, especially because of damage by lightning. In fact it is very difficult to design a signal operating upon a grounded circuit which will not be seriously affected by lightning. The widely varying voltages on the various sections of the average interurban line also introduce difficulties in the design of signals to be operated from the trolley circuit. It should be noted that in both of the above systems the motorman is assured that the red signal has been displayed at the farther end of the block if the green light appears at the entering end. This fact is seldom determined by the steam railroad engineer who relies upon the automatic block signal to give the danger indication without actually observing the signal movement himself.

A signal system very similar to the above is manufactured by the Nachod Signal Company. In addition to the above protection, however, this signal counts the cars into the block as they enter and does not return to "clear" until each car has been counted out. An indication is given the motorman by means of the flash of a lamp that his car has been registered as the trolley switch is passed although the signal aspect remains unchanged. A further protection is offered in this system in that the signal may be made an "absolute block" system by manually opening one of the line wires by means of a pole switch, thus causing red signals to be displayed at both ends. This provision is of convenience when a line repair crew is working in the block.

Still another type of signal similar to the above displays an orange-colored light when no car is in the block and a green cautionary light as the car enters in series with the red danger signal at the distant end. The principal difference in the operation of this signal is that it makes use of a single rail with each block insulated from its neighbor as far as the flow of signal current is concerned, as will be explained later in connection with single rail automatic block signals.

Automatic Block Signals.—The signals described thus far have been installed on sections of single track between sidings to control and protect cars operating in both directions. In distinct contrast to these is the automatic block signal used to protect cars on sections of double track from the danger of operation with too small headway and yet to permit the minimum safe headway to be maintained under conditions of heavy traffic. This is the type of signal used to an ever increasing extent on steam trunk lines, although the details of design vary somewhat when applied to electric service. While the large interurban systems of the Middle West are just beginning to consider seriously the question of equipping their lines with automatic block signals, this type of signal has for a long time found a most important application in elevated and subway installations in the largest cities of the country. A rather detailed study of this type of signals, therefore, is very appropriate at this time.

A "block" as the term is used in this discussion, may be defined as a section of track so protected that but one train can be in that section at any given time, no other train being allowed to enter until the last truck of the previous train has left the section. The length of these protected blocks will be determined in each particular case. They must be sufficiently long to enable a heavy high-speed train to stop within their limits and yet sufficiently short to permit the smallest safe headway between trains during rush hours. They usually vary from 2000 ft. to 2 miles in length.

At the entrance to each block a signal must indicate, both by day and night, whether or not there is a train in the first block beyond. Such a signal is termed the "home" signal. In addition it has been found advisable, if high speed trains are to operate smoothly without frequent periods of slow-down, to install an additional signal, usually upon the same standard as the home signal, to indicate the condition of the second block ahead. This signal is termed the "distant" signal.

These indications are usually given in daylight by means of a semaphore and with colored lights at night. As considerable trouble has been experienced from the use of colored "bulls-eyes" or signal "roundels" at night upon roads using the very

powerful headlights owing to reflections from unlighted roundels appearing as signals, it is believed that if the more powerful headlight is adopted the semaphore or "position" signal will be ultimately very generally used as a night signal as well, being sufficiently well illuminated by means of the headlight to permit the accurate reading of signal aspects.[1] The semaphore when in a horizontal position indicates "danger," while the "proceed," or "clear" signal is usually indicated by a 60° angle in the lower quadrant. In some types of signals three angular positions are used, a 45° position indicating "caution" and a vertical position "proceed" or "clear" aside form the "danger" indication. In a few instances, and upon the Pennsylvania railroad in particular, the "clear" position is represented with the semaphore in the upper quadrant, the arm falling to the horizontal position by gravity to indicate "danger" or when anything is wrong with the signal apparatus. Such a signal is designated as a "normal danger" signal as contrasted with the "normal clear" types described above. Each has its rather obvious advantages and disadvantages and therefore its ardent supporters among signal engineers. The corresponding signals at night are usually red for "danger," green for "clear" and yellow for "caution," although the two latter colors vary somewhat for the different roads.

As the train arrives at the entrance of a block the home signal denotes the condition of the first block and the distant signal that of the second block ahead. With both at "danger" the two blocks ahead are occupied and the train stops. With the home signal at "clear" and the distant signal at "danger," the first block is clear and the second occupied. The train may enter the block under control. With both signals at "clear" the engineer knows that two blocks ahead at least are clear and he may enter the block at full speed. The distant signal at the first block and the home signal of the second block are so interlocked that the former cannot move to "clear" until the latter has attained a similar position. Upon entering the first block under control with the distant signal at "danger" it is expected that the next

[1] "Headlight tests" by Professors C. F. Harding and A. N. Topping, A. I. E. E., Vol. XXIX.

home signal will be at "danger." Since, however, the signal may have changed before the train reaches the second block, it is often advisable to install a second distant signal within safe stopping distance of the second block. This is especially true if the second block signal is not readily seen at some distance, since it avoids slowing down if the second block has been cleared in the meantime.

While it is unnecessary to describe in detail the operating mechanism of the semaphore and colored roundels in its various forms, it may be said that this movement is accomplished by means of mechanical levers and bell cranks, gas or air pressure operating pistons in cylinders located in the base of the signal, or by electricity used through the agency of a solenoid or series motor. The control of the local apparatus at the signal by means of electric relay circuits is, however, of greatest importance and will be explained in detail.

Steam Railroad Practice.—As the block signal systems used with electric roads have been patterned after the more simple steam railroad installations a description of the latter will aid in understanding the former. The two rails for a block in length are insulated from one another and also from the adjacent rails of neighboring blocks by means of insulating rail joints. The various rail lengths of a single block are bonded together in a manner similar to that described in Chapter VI, but with much smaller wire bonds. A gravity or storage battery of 1 or 2 volts e. m. f., located in a manhole below the frost line, is connected between the rails at one end of the block. At the other end of the block a sensitive relay is connected across the two rails. This relay is usually mounted in the base of the signal tower and thereby protected from the weather. Where there is no train in the block the battery supplies current to the relay by way of the two rails and the signal is held in the "clear" position. As the first trucks of a train enter the block, however, the wheels and axles short-circuit the relay and it opens, closing the local circuit which throws the semaphore and colored roundels into the "danger" aspect. The signal is locked in this position until the movement of the last truck of the departing train from the block removes the short circuit, closes the relay, and clears the signal.

Such is the very simple circuit and mechanism of the automatic block signal for steam railroads and although its first cost has been sufficiently high to render its adoption rather slow, its maintenance is not excessive and its positive operation is to be depended upon. In fact in one instance but one failure to operate in 250,000 was the record of operation on a large signal system during the period of one year.

Electric Railroad Block Signals.—With the electric railroad, which makes use of the track rails for the return of heavy currents to the substation or power house, the problem becomes a more difficult one, as the rails are no longer free for sectional insulation

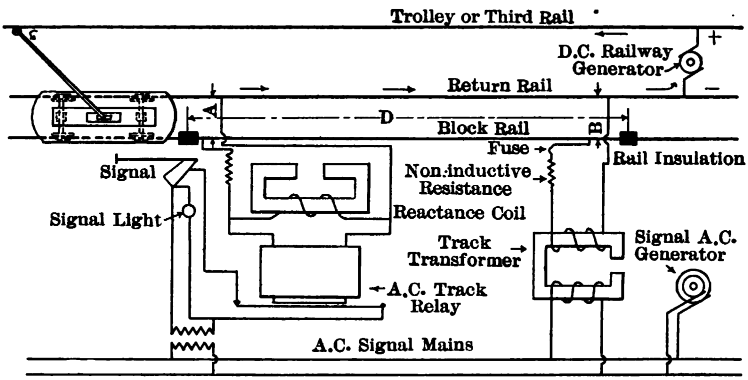


FIG. 76.—Single rail alternating current block signal.

as in the case of steam roads. One method of overcoming this difficulty which would naturally suggest itself is to use one rail for signal purposes and the second rail for the return of power current. The further use of alternating current for the signal relay would permit selective operation of the latter without interference from the power current. Such a system is successfully used in the New York subway, its principle of operation being illustrated by Fig. 76.

By referring to the above figure it will be seen that one rail termed the "block rail" is insulated in sections, one block in length, constituting a circuit for signal current only. The other rail carries the current from the trains and also acts as a common return circuit for the signal system. Alternating current for the signal circuit and also for the signal lamps is supplied through

transformers from single-phase alternating current mains paralleling the track. If the power current is flowing in the return rail from left to right the voltage between rails at (B) will be slightly less than at (A) due to the fall of potential in the rail. This will cause some of the direct current to pass through the relay connected between the rails at (A), thence through the block rail and the transformer secondary to the return rail at (B), the latter forming a high resistance shunt path to the length of return rail (AB). In order to limit the amount of this current which would otherwise produce a uni-directional magnetic field

FIG. 77.

in the relay and transformer, high noninductive resistances are inserted in series with the relay and transformer secondary and a reactance coil shunted across the relay. While the direct power current following the block rail will pass freely through this reactance, the signal alternating current will be prevented by the impedance of the reactance coil from taking that path and will therefore pass through the relay. As an additional precaution in the case of the transformer an air-gap is introduced into the magnetic circuit to reduce to a minimum any magnetic flux which might be produced by the relatively small leakage direct current.

With these added precautions the relay system operates exactly as in the case of steam railroad equipments with the exception that the relay must be of the alternating current type. A relay depending upon the torque produced by eddy currents induced in an aluminum disc being acted upon by the magnetic field set up by the current in the relay has been adopted for this purpose.

In the case of the particular installation of this system in the New York subway, the alternating current distribution is at 500 volts and 60 cycles, the track transformers stepping the potential down to 10 volts, while the signal lamps are operated at 55 volts. The resistance of the track and signal circuit is such as to impress approximately five volts upon the relay. The power factor of the circuit is in the neighborhood of 80 per cent. and the power taken by an average block but 80 watts. A typical installation is represented in Fig. 77.

Block Signals for Alternating Current Roads.—When the problem arose to equip electric roads operating with alternating current in the track rails, it may be readily seen that still further difficulties were encountered. The problem was fairly well solved, however, by the development of the two rail signal system making use of inductive bonds, although this equipment can hardly be considered in a state of perfection as yet. It has been adopted as well in some instances on direct current roads where the full conductivity of the two rails was considered of sufficient value to overcome the slight disadvantages of a system requiring the use of inductive bonds.

The principle of this type of signal system, similar to that operating on the single-phase terminal electrification of the New York, New Haven and Hartford Railroad in New York, is illustrated in Fig. 78. It will be seen that each rail is insulated at the ends of the block as in the case of steam railroad practice, but inductive bonds are installed between the rails at (AB) and (EF) of sufficient capacity to carry the train current. The middle points of adjacent bonds are connected together so that there is a complete electrical circuit from train to power house by way of each rail, this circuit involving one-half of each bond at every block. These bonds are carefully designed so that their counter e. m. f. will not be great at the frequency of 25 cycles or

below, at which the train motors operate, but will be sufficiently great to produce a useful difference of potential between the rails in the signal circuit which is operated at 60 cycles. In other words a very interesting application is made of the theory that the reactance of a coil is proportional to the frequency and the bonds are therefore designed to operate upon one frequency only.

The immediate source of power is the transformer as in the single rail system, but in this case the power current is sufficiently well balanced in the two rails to prevent unbalanced currents flowing in the transformer and the air gap in the magnetic circuit

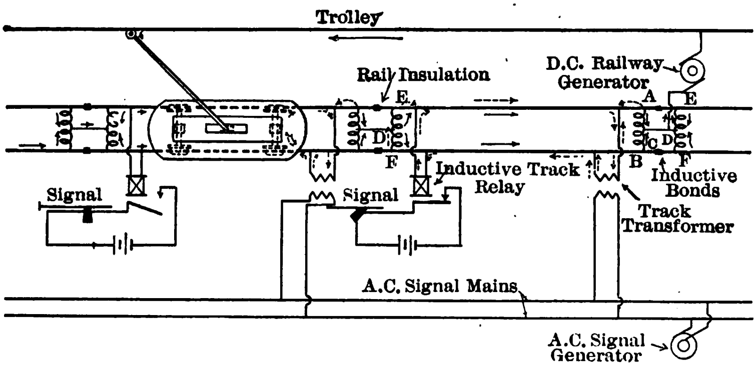


FIG. 78.—Double rail alternating current block signal using inductive bonds.

is therefore omitted. The transformer is designed with a relatively high leakage factor, however, in order that the current may not be excessive when the secondary of the transformer is short circuited by the train in the block. It will be noted further that for the above reasons the auxiliary resistances and reactance shunt across the relay may be omitted.

With these changes and a slight change in the design of the relay, the system operates as in the single rail design. The direction of the power current is shown by full lines and that of the signal current by dotted lines in Fig. 78.

In all of the above automatic block systems it should be noted that if the track relay circuit be opened the action is the same as though the relay were short circuited by a train in the block, *i.e.*, the signal is thrown to "danger." This action has proved of great value in detecting broken rails and has probably prevented a number of wrecks thereby.

In a few instances this type of signal has been used on single track blocks, but here the difficulty lies in not being able to tell which way the train is moving that is occupying the block, while in the double track system, if the block were not cleared in the usual time, the train might move forward slowly in order to locate the trouble, with the knowledge that the train ahead was headed in the same direction. In the case of the single track, however, it would be necessary to send a flag-man ahead to prevent a head-on collision if such an investigation were attempted. It is probably for this reason, together with the larger percentage cost of block signals, that they have not been widely installed on single track roads. Upon the Harriman lines, however, where they have been used to a considerable extent on single track it is claimed that their detection of broken rails as above explained has well warranted their installation.

Cost.—The Electric Journal is authority for the statement that the average cost of an automatic block signal system, with combined home and distant signals on a single standard will vary from $750 to $1100 per block, depending upon the length of block, number of switches, and method of signal control. An average value for maintenance has been placed at from $75 to $100 per annum for a two-arm signal.

It may have been inferred from the previous discussion that there is a wide variety of signal systems with widely varying degrees of protection and corresponding first costs, from which to choose. While a theoretically perfect system has not yet been developed, it is safe to say that the more complete systems have not been cast aside by the interurban railroads because of their unsatisfactory design and operating qualities, but rather because of their high first cost and maintenance charges. As the combined result of some rather serious wrecks which have recently taken place on interurban roads, the advertising value of a complete automatic block signal system and the increasing pressure which is being brought to bear by state railroad commissions throughout the country, it is believed that the automatic block signal will be pretty generally adopted in the near future and the resulting developments in the electric signal field correspondingly rapid.

PART III.

EQUIPMENT.

CHAPTER I.

Track Layout and Construction.

The electrical engineer of a proposed electric interurban railway is often called upon to determine the right of way and superintend the track survey and construction, although in the large city systems or extensive interurban developments a technically trained civil engineer is usually given this responsibility. In either case the electrical engineer should be familiar with such general features of the problem as may be herein outlined.

Right-of-way.—After several proposed routes have been suggested for the new railway, possibly with the aid of rough preliminary surveys for each, and detailed notes taken of the advantages and disadvantages of each, involving the typography of the country, number of intermediate towns and amount of tributary population served, possible schedules, etc., it is necessary to decide upon one route. This is usually determined by the officials of the company in conference with the engineer. With this decision in mind the problem of obtaining the right-of-way presents itself and it is often policy not to make the above decision public until after the greater portion of the right-of-way has been secured. In fact it has sometimes been found advisable to propose publicly two possible routes and even go to the extent of purchasing options on land along each in order that an element of competition may enter, preventing land and options from assuming exhorbitant values along the desired route.

Great diplomacy must be exercised by the advance real estate agent in order to secure the desired route at a reasonable figure and without too many concessions, which often complicate the schedules and embarrass the company when operation begins. It must always be remembered that much of the future traffic will come from those with whom these preliminary negotiations are made.

If satisfactory locations cannot be secured, either because of

opposition to the proposed road or too high prices being placed upon the land, right of eminent domain may be secured through the court and certain sections of the route condemned and thereby purchased at a value appraised by the court or a commission appointed by the court. As this proceeding makes public the proposed route and prejudices some against the company, it should be avoided if possible, but if found necessary, it should be postponed until the remainder of the land has been secured.

It will be noted that the above discussion presupposes a private right-of-way for the road. Such a route is generally much to be preferred except within the limits of intermediate towns, and even in the latter case a route but a few blocks from the center of town on a back street with little traffic, where speeds may be fairly high and frequent curves avoided, should be given serious consideration. In some instances interurban railroads run for miles along country roads, but it is usually done at the expense of low schedule speeds, and high maintenance charges due to restrictions often imposed by town boards and street commissioners, not to mention frequent and serious accidents. A slightly larger first cost for a private right-of-way is justified in most cases from the standpoints of schedule, safety and independence from ordinances stipulated by outsiders not only, but from the purely financial consideration as well.

A right-of-way at least 100 ft. in width should be secured to allow for possible double track with necessary cuts and embankments provided with adequate drainage ditches. Such a strip of land averages twelve acres to the mile.

With the route approximately determined and the right-of-way secured, a final survey should be made to locate the exact line for the track and to determine the profile. With the exact profile plotted the grade line may be drawn consisting of an average line through the profile representing a series of grades, with none exceeding 2 per cent. if possible, and with as close a balance between "cuts" and "fills" as may be secured in order that the haul for excavation and embankment may be a minimum. While grades as high as 7 or 8 per cent. sometimes exist on interurban roads it will often be found that when the first cost of the extra heavy car equipment and possibly the

station equipment necessary to climb these grades, together with the annual cost of extra power required are balanced against the fixed charges on the extra cost of reducing the grade by means of a deeper cut or a slight change of route, the latter policy would have been the better of the two.

Before accurate estimates can be made or contracts let for preparing the sub-grade it will be necessary to learn something more of the character of the sub-soil. It will be assumed that the general nature of the country and its geological formation were carefully noted during the preliminary survey, since the decision of the proper route depends largely upon such a study, especially when a river is to be paralleled and possibly bridged occasionally. It is now necessary, however, to have test borings made as deep as the deepest proposed cut at intervals along the line sufficiently frequent to obtain a good idea of the type of excavation to be

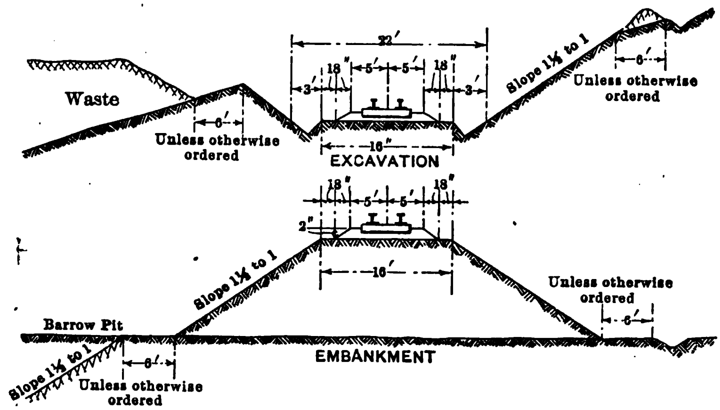


FIG. 79.

expected and the necessity of driving piles or installing mattress concrete or timber in case of possible quick sand. A contract can usually be placed for such borings with their results either represented to scale on a drawing for each station or better by a glass tube filled to scale with the various strata of sub-soil found.

With this information at hand a series of cross sections at right angles with the base line at stations 100 or 200 ft. apart, or possibly less where the profile is very irregular, may be made and the volume of excavation and embankment calculated. A list of cut

and fill expressed in cubic yards of each type of sub-soil from solid ledge to soft clay may then be made for each mile of road and estimates readily calculated and contracts signed. Typical sections of cuts and embankments will be found in Fig. 79, while estimates of their respective costs in the South will be found at the end of the chapter. These latter values vary greatly with local conditions and are usually based upon a certain maximum length of haul between a cut and the corresponding fill into which the excavated material may be deposited.

Ballast.—It is safe to say that the experience of interurban roads which have been operating for some time demonstrates the fact that money expended in first class sub-grade construction and rock ballast proves to be the most economical in reducing maintenance charges and providing a smooth riding roadbed which does not quickly wear out both itself and the rolling stock.

The ballast, which is that portion of the roadbed upon which the ties are placed, should be sufficiently porous to permit the water to run off freely. The best ballast is recognized to be crushed rock capable of passing through a 1 1/2 in. ring. Coarse gravel, however, makes a very good substitute and is very often used because of its lower cost. Fortunate indeed is the road that secures with its right-of-way one or more borrow pits containing good ballast gravel. This ballast is laid for a depth of 6 to 18 in. under the ties and should cover the ties to the base of the rail.

Ties.—Now that the scarcity of good lumber is beginning to be felt, with a corresponding increase in first cost, the selection of suitable ties and their treatment to insure long life is becoming a serious problem. Pine, cedar, white oak, red oak, fir and chestnut are the woods in most common use. The choice between these depends largely upon the variety which is native in the locality in which the road is being built. Cedar is probably as long lived as any, while the ability of white oak to hold spikes is probably greater than any other wood. While this variety of tie is generally too expensive to use throughout, it is often specified for curves where the strain on spikes is of course greatest.

Herrick gives in the following table an approximate length of life for the different varieties of ties as determined by Mr. Hough[1]

[1] "Practical Electric Railway Handbook," by A. B. Herrick.

TABLE XVIII.

LIFE OF TIES.

White oak	7.4 years.
Red oak	5.0 years.
Chestnut	7.1 years.
Southern pine	6.5 years.
White pine	6.5 years.
Red cedar	11.8 years.

It is generally considered advisable to specify preservative treatment for ties in order to increase their life, although it is difficult to determine from experience thus far just how much the life is extended thereby. Probably a fair average price for an untreated tie throughout the country is 70 cents with a possible 15 cents per tie increase for treatment. Ties which have been embedded in concrete in city construction have shown particularly long life, averaging from 10 to 20 years with many rail replacements. The replacement of rails and removal and replacement of spikes during realignment often shorten the life of a tie when it has not decayed. Screw spikes have been proposed to obviate this difficulty, but they are little used at present because of their higher first cost and the greater time required for installation and removal.

Reinforced concrete and steel ties have been experimented with, especially abroad. Whereas concrete and steel substructures are replacing ties to a large degree in city streets the wooden tie for interurban or steam railroad use has not been replaced to any extent in this country.

The dimensions of ties for interurban use are similar to those for steam roads, averaging $6'' \times 8'' \times 8'$, although 5-in. ties may be found occasionally. In third rail construction a longer tie is installed every 10 ft. to act as a support for the third rail insulator. The spacing of ties will be found to vary from 15 to 30 in., but an average dimension may be taken as 2 ft. Ties which lie under the rail joints are placed nearer together, but their exact spacing is dependent upon whether a suspended or supported rail joint is used, as will be described later.

One consideration in connection with the selection of ties which has received very little attention is the effect of preservative treatment upon their resistance. This is of particular value

only where the automatic block signals are installed. From the discussion of the previous chapter it will be seen that if the resistance of the ties be greatly reduced they will act as a shunt to the relay and possibly interfere with its proper operation. Tests recently made at Purdue University[1] upon the resistance of ties recorded in the report of the wood preservation committee of the American Railway and Maintenance of Way Association prove

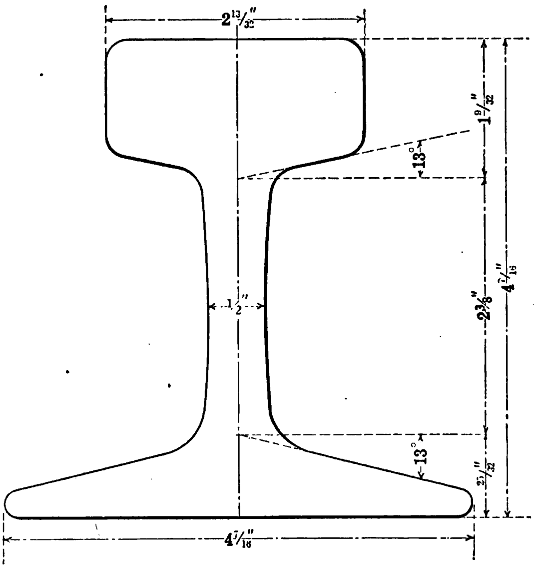


FIG. 80.

that ties follow the laws of insulators in general, but that when treated with the chloride of zinc preservative process their apparent resistance is lowered. Calculated results based upon the data of these tests, assuming wet treated ties in wet ballast, show values of resistance sufficiently high to prevent serious interference with signals. Cases in practical operation have been reported, however, in which such interference has been present.

Rails.—In the selection of rails also, steam railroad practice has been followed to a great extent, although the weight of rail used is, on the average, less with the interurban roads. This is

[1] Graduate Thesis, Purdue University, by J. T. Butterfield, 1910.

possible because of the lighter weight of trains and the absence of reciprocating motion. The interurban roads make use of the "T" rail almost exclusively, averaging in weight from 70 to 80 lbs. per yard. The section which has been very generally adopted is the standard established by the American Society of Civil Engineers as shown in Fig. 80. In city streets a wide variety of rail sections will be found from the "T" rail to the various shapes and sizes of grooved girder rails. The "T" rail has been rather

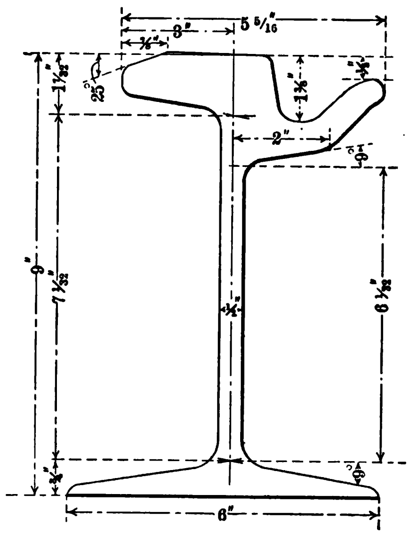


FIG. 81.

generally objected to by city authorities because of the danger to vehicular traffic offered by the projecting head of the rail and the difficulty in paving close to the rail with standard paving blocks. Two sizes of girder rails 7 in. and 9 in. in height respectively have come into general use, the latter being preferred from the standpoint of ease in paving. At the 1910 annual convention of the American Electric Railway Association the 9 in. standard girder rail illustrated in Fig. 81 proposed by the Committee on Way Matters was adopted as well as a similar 7 in. section. These are designed for installation in city streets where the traffic is particularly heavy.

The proper chemical composition of rails has been a ques-

tion under discussion for some years, attempts being made to obtain a hard rail which shall not be so brittle as to break readily. Low conductivity is also a desirable, although not a governing feature. The analysis which has been standardized by the American Electric Railway Association is given in the following table:

TABLE XIX.

STANDARD ANALYSIS FOR STEEL RAILS.

	Lower limit.	Desired composition.	Upper limit.
Carbon	0.6%	0.68%	0.75%
Manganese	0.6%	0.80%	0.90%
Silicon (not to exceed)			0.20%
Phosphorous (not to exceed)			0.04%

The above table applies to open-hearth steel, as the majority of rails are now being manufactured by the open-hearth process.

The composition of the third or conducting rail may be such as to result in a much softer and lower resistance rail. Armstrong gives the following analysis for such rails.

TABLE XX.

[1]ANALYSIS FOR THIRD RAILS.

Carbon not to exceed	0.12 per cent.
Manganese not to exceed	0.40 per cent.
Sulphur not to exceed	0.05 per cent.
Phosphorous not to exceed	0.10 per cent.

The use of manganese steel for the centers of special work and even for complete frogs, switches and curves has been recently given a great deal of attention because of its long life. While it seems to be the consensus of opinion among railway operators that the latter uses of manganese steel are only advisable in extreme cases of heavy wear, the adoption of replacable frog and switch points of this material is very heartily sanctioned.

The method of laying rails in city streets departs greatly from

[1] Electric Traction by A. H. Armstrong.

interurban practice, a liberal use of concrete, steel and sand in the sub-grade being common practice. Rails are often temporarily supported upon wooden ties spaced 5 ft. or more apart in order to hold them to gauge while concrete longitudinal stringers are being installed for the final rail support. Iron chairs embedded in the concrete serve to grip the rail flanges after the concrete is set. Less elaborate installations involve the use of the usual number of wooden ties laid in concrete. This construction has been adopted as shown in Fig. 71 in Chicago, where it has been the policy to construct a permanent foundation from which the rails may be removed from time to time and new rails installed. This rigid construction of the roadbed is at variance with the method of at least one of the largest steam roads whose engineers believe that the roadbed construction should be somewhat flexible in a vertical plane, being depressed slightly as the train passes, but returning to its original position thereafter.

Rail Joints.—Aside from the mechanically rigid rail joints produced by cast welding, thermit welding and electric welding discussed in some detail in Chapter VI, Part II, several other types of rail joints in rather more common use should be mentioned. The simplest and cheapest joint is of course the four or six bolt fish plate clamped on either side of the rail ends. This construction allows considerable vertical motion to the ends of the rails as the train passes over them, causing the heads to be soon flattened. The rail must therefore be replaced or shortened because of its worn condition at the end before it is seriously worn elsewhere.

The other types of joints most commonly used are the Atlas, Continuous and Weber joints, all of which make use of combined splice bars and tie plates differing but slightly in design, *i.e.*, they all furnish an iron plate between the foot of the rail and the tie, which plate is generally notched to receive the spikes in order to prevent creeping. The Weber joint makes use of a single plate cast in one piece with one of the vertical plates while the other joints involve two half plates split longitudinally under the center of the rail.

The use of tie plates is a matter open for discussion. They probably increase the life of the ties, especially when rather soft

wood is used, by preventing chafing between rail and tie, but many engineers are not convinced that this gain warrants the extra expense.

Rail joints may be of the "suspension" or "supported" type, the former having the rail ends between ties, while the latter provides a tie directly under the ends of the rails. The former seems to be in more general use. In case the Atlas rail joint be selected the suspension type must be used, as this joint requires transverse bolts through the casting under the rail flanges at the end of the rail.

Both 30 and 60 ft. rail lengths are in use, the former being preferred in interurban construction because of less expansion troubles therewith and the greater ease of handling the shorter length on curves. Where the above features are not objectionable, however, the 60 ft. rail has the advantage of fewer joints and bonds, thereby reducing slightly the first cost and maintenance charges.

Rail Corrugation.—Quite recently a peculiar corrugation of the heads of rails, particularly near the joints, has been reported by many companies and in many instances special grinding devices have been designed to remove such corrugations, but in spite of extended study and discussion of the question no satisfactory reason for the effect has been found. It has been variously attributed to chattering of brake rigging upon stopping the car, the transverse nosing of trucks, the peculiar chemical or molecular structure of the rails and the possible formation of successively soft and hard spots due to some peculiarity of the rolling process. As this effect has been found under practically all conditions, rails of one particular make or in any particular position in the roadbed cannot alone be charged with the difficulty.

Paving.—The railway company is usually required to install and maintain the pavement between tracks and for a distance of 2 ft. or more outside. If paving blocks are used with anything but a 9 in. girder rail a special block must be secured to fit the rail and provide a groove inside the rail sufficient to allow the wheel flange to pass without forming a dangerous rut for vehicular traffic. Such grooves are rapidly worn away by the latter traffic and the railway company endeavors, therefore, so to design the

track and paving that the vehicles will not be attracted thereto. This policy will often aid in making schedule time in city streets as well. With the grooved girder rail the groove provides room for the flange. Fig. 71 well illustrates paving construction with this type of rail.

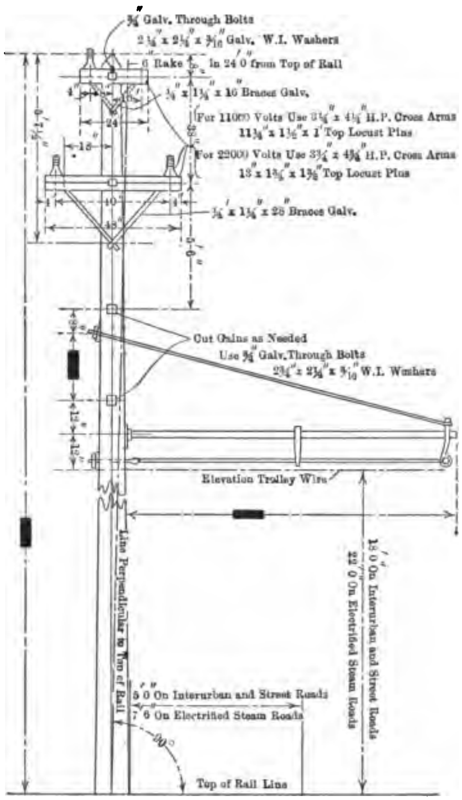


FIG. 82.

Overhead Construction.—Typical bracket and span overhead construction are now so familiar to all, little description is necessary aside from the specifications given in Fig. 82 and 83, the former representing the single track bracket standard construction of the Connecticut Company, while the latter is typical of double track span construction with two high tension transmission lines.

Neither of the above illustrations, however, shows the details

of the trolley insulation and hangers. It is customary at present to use grooved hard drawn trolley wire with mechanical clamps or ears which spring into the grooves in the wire and are clamped therein by means of four machine screws. Much time is thus saved in repairs over the old soldered ears. Double insulation is provided between pole and trolley by means of the insulating hanger and strain insulators in series. Strain insulators in span construction should be sufficiently near the trolley

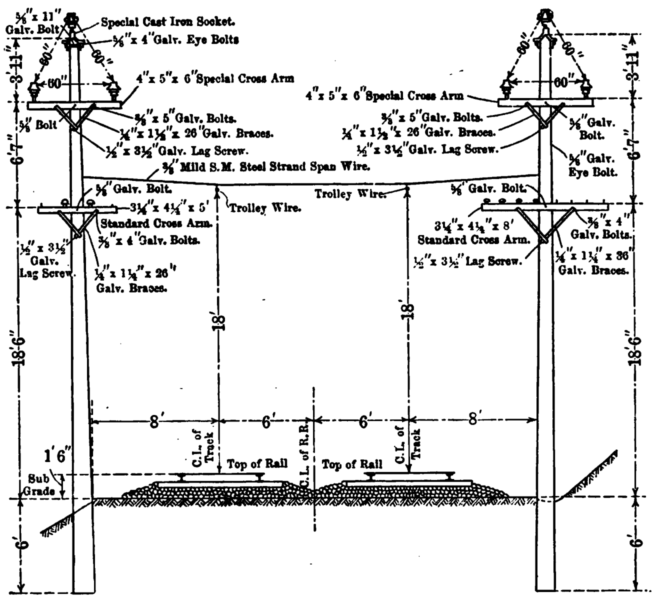


FIG. 83.

so that a broken "live" span cannot reach the ground and yet sufficiently far away so that a trolley pole when off the wire cannot impress full potential upon the span outside the strain insulator.

Catenary line construction, which is meeting with favor even for low voltages, was described in a previous chapter.

Lightning protection is provided for the trolleys and feeders by mounting a low voltage lightning arrester on the pole top at distances apart varying with different companies from 1000 ft. to several miles. Grounds for such arresters should be thoroughly made by burying a plate of copper or an amount of scrap

copper wire of large surface area in coke in permanently moist earth and connecting the arrester with this ground by means of a straight copper wire of at least No. 4 B. & S. with well soldered joint stapled to the pole. Fairly good results have been obtained in new construction by winding copper strip about the butt of the pole before installation and in some cases with a long pipe driven into the ground containing a plug into which the ground wire is soldered. The practice of grounding lightning arresters to the rails should be discontinued as it has been found to destroy the arresters without giving the necessary protection.

Poles are usually spaced from 80 to 125 ft. apart, the smaller distance being used on curves. Poles should be guyed on curves and anchors or longitudinal guys installed to support the line at least every mile. With the present cost of lumber it seems worth while to treat the butts at least with preservative compound and often to treat the entire pole. The poles should at least be kept well painted even on interurban lines. Iron poles have found a place in city streets principally because of their better appearance. Corrosion can be held in check by painting frequently and by setting butts in concrete. In fact, the latter method is often used for the protection of wooden poles even after they have begun to decay at the surface of the ground.

Estimates.—Whereas the cost of materials varies so greatly in different portions of the country, estimates or actual costs of construction must be taken with a great deal of caution. They seem to be of sufficient value as a study of approximate relative values, however, to warrant listing herein. Such an estimate covering the construction for an interurban line 63 miles in length in the South will therefore be found on page 218.

The estimate represents an expenditure of $13,700 per mile for roadbed and track exclusive of engineer's fee and contractor's profit. It is interesting to note that of the above total 37.8 per cent. is labor and 62.2 per cent. material.

ESTIMATED COST OF ROADBED CONSTRUCTION.

	Labor.	Material.	Total.
Clearing and Grubbing.			
68 acres at $45	$3,060	....	$3,060
Grading.			
Solid rock 8000 yds. at $0.75	6,000	....	....
Loose rock 35000 yds. at $0.37	12,950	....	....
Earth, 716000 yds. at $0.145	103,820	....	122,770
Culverts.			
150 Culverts varying from 18″ to 60″ diam. Total 4573′.	....	9,420	....
Hauling and placing	995	....	....
End walls 1300 yds. at $8	10,400	....	20,815
Timber bridges.			
41 Pile bridges, 4752 lin. ft. at $8.80	14,000	27,818	....
1 Frame bent bridge, 800 lin. ft. at $10.25	2,730	5,470	50,018
Steel Bridges.			
9 Steel spans ranging from 30′ to 130′, 700520 lb. erect. at 4 1/8 cents.	3,502	25,395	....
Concrete piers, 2300 yds. at $7.20	8,280	8,280	....
Deck, 2300 yds. at $2.50	675	1,300	47,432
Track.			
Rail 80 lb. 33′, 8431.7 tons at $33.515	....	282,588	....
Angle bars, 21690 prs. at .86	....	18,653	....
Track bolts, 86762 at .04	....	3,471	....
Track spikes, 2010 kegs at $5.60	....	11,256	....
Bonds, 21160 at .60	3,196	9,500	....
Cross bonds 67 total	....	....	600
Track ties, 169860 at .65	....	110,409	....
Switches compl., 18 at $150	....	2,700	....
Labor	26,548	....	468,921
Ballast.			
Local gravel or lime rock	130,000	....	130,000
Fencing (Wire).			
26900 rds	5,380	11,112	16,492
Miscellaneous.			
Railroad crossings at $300	200	1,000	....
Highway and Private crossings at $47	1,150	4,490	....
Signs	100	300	7,240
Grand total			$866,748

CHAPTER II.

Rolling Stock.

Notwithstanding the fact that electric traction has been developed within a comparatively few years, cars which are now operated upon the various city and interurban lines of the country range from the 20 ft. single-truck made over horse-cars to the 60 ft. magnificent limited double-truck parlor cars weighing from 40 to 50 tons and provided with all the conveniences of the Pullman coach. With this array of possible rolling stock to choose from the problem of car selection for a proposed road or for additions to present equipment on city or interurban systems is a difficult matter. Too little attention has been given to this problem in the past, the questions of sufficient seating capacity and finish often being the principal considerations in the selection of cars. These factors are of course of prime importance, for the public patronage is not only dependent upon the ability to obtain a seat in a car, especially upon a long journey, but also to a surprising extent upon the appointments of the cars with respect to personal convenience. That there are several other very important factors to be taken into account, however, will be made clear in the following discussion.

With the gradual increase in speed of cars there came an increasing number of wrecks which soon proved the average car construction to be unsuitable for withstanding severe strains and thereby protecting passengers to some extent from injury in case of collision. Then came a period of marked increase in the weight of cars with correspondingly increased capacity of car equipment not only, but of feeders, and substation and power station capacity as well. Quite recently, however, another reaction has taken place, for it has been found that the desired strength to resist the abnormal forces in service may be obtained by proper design with even less weight. This apparently paradoxical condition is partly due to the fact that the use of steel in

place of wood will give greater strength with less weight and also for the reason that a car may be considered as a double truss, the side frames acting as one truss to transfer the load to the bolsters and the bolsters in turn acting as transverse trusses between the car sills and the truck support. For steel frame construction see Fig. 84.

The desirable reductions possible in cost of power, car repairs, track repairs, fixed charges on power plant and distribution

FIG. 84.

system with decrease in weight of cars are very clearly pointed out in a paper by M. V. Ayers, electrical engineer of the Boston & Worcester Street Railway before the American Street and Interurban Railway Engineering Association in 1909. In this paper formulæ are developed for the above cost reductions and suggestions given for the possible decrease in weight of cars without a curtailment of strength. Aside from the above truss design and steel under framing, the use of aluminum and cast bronzes in place of iron, soft woods in many places instead of hard woods and the reduction in the weights of motors with forced ventilation are mentioned.

Another very marked advance is the standardization by the above association of the heights of underframes of both interurban and city cars and the use of corrugated iron buffers on the latter extending to the height of the sills of the former cars to prevent telescoping of platforms in case of collision. Such telescoping was the cause of much damage in several recent and very serious interurban wrecks in the Middle West.

Motor Equipment.—The question of whether a two or four motor equipment should be installed must be given careful thought. Previous chapters have described the method of determining the total power required for the car, but whether this should be supplied by two or four motors is quite another problem. With single truck cars two motors only are possible. In the case of double truck cars four motor equipment is probably most commonly found, although many roads are operating with but one motor per truck. Tests which have been made with the same car equipped in both ways disclose the fact, which might be theoretically predicted, that the four motor equipment will require less power for the same schedule. This is largely due to the distribution of torque over the larger number of driving wheels. This torque distribution as well as the reserve capacity over that called for by the theoretical calculations, especially under the abnormal conditions of snow fighting and making up lost time, are usually considered of tangible monetary value by traction managers.

For these reasons the four motor equipment has generally found favor. While the control equipment and car wiring are slightly more complicated with the four motor equipment the ability to use two motors, ordinarily with one on each truck, in case of failure of one or more of the other set is worthy of consideration. In short the continuity of service and maintenance of schedule speed must be thought of as well as first cost of equipment and operating expense.

Trucks.—The truck primarily consists of two pairs of wheels and axles upon whose journals a steel framework is supported by means of combined spiral and elliptical springs. This framework serves to take the weight of the car body not only, but to form a support for the brake rigging and a portion of the weight

of the motors as well. Since the axles are held in a position parallel to each other by the fixed journal boxes the distance between axles cannot exceed a certain value, generally 7 ft. 6 in., because of difficulties in following curves of short radius in the track. With this limitation and with the further fact demonstrated by practice that single truck cars tend to rock badly in the direction of motion, the length of single truck car bodies must necessarily be limited to from 22 to 25 ft. overall. For the longer cars two trucks with king pins located as near the ends of the car as possible without interfering with vestibule supports must be used.

With either type of truck the motors are suspended with two babitted boxes, cast in one side of the motor frame, bearing on the car axle and the opposite side of the motor is hung by means of a flexible link from the truck frame. The so-called "nose" suspension provides but one support between motor and frame, while the "yoke" suspension, as the name implies furnishes two such connections. With these suspensions the motor is permitted to swing slightly about the car axle as a center as the car passes over irregularities in the track, thus keeping the pinion on the motor shaft at all times in mesh with the gear on the car axle.

Trucks are provided with car wheels ranging from 33 to 37 in. in diameter, the larger sizes being generally used in heavy interurban traction. Wheels are constructed of cast iron with chilled treads, cast steel, or a combination of cast iron centers with steel rims. The latter type has now been largely replaced on interurban roads by the cast steel wheel, as some difficulties were encountered due to the steel rims working loose in service. Wheels may be returned four or five times before scrapping is necessary, a reduction of from 3/4 to 1 in. in diameter being possible before wheels must be discarded. Steel wheels will range from four to five times the mileage of cast iron wheels and the latter are considered unsafe above 30 m. p. h. Wheels varying as much as 2 in. in diameter have been successfully used on different axles of the same car, although those on the same axle must be of the same diameter. The wheels are forced on the axles under hydraulic pressures of from 25 to 50 tons, depending upon the type of wheel and size of axles.

Car axles are turned from cold rolled steel and vary in diameter from 4 in. with the smallest motors up to 7 in. with 200 and 250 h. p. motors in heavy service.

Lubrication is ordinarily provided to the half bearing by means of cotton waste soaked in grease with which the journal box is packed, although within the last few years an apparent saving has been made on some roads by adapting the journals to oil lubrication.

Trucks are provided with side bearing plates upon which similar plates on the under side of the car may rest when the latter is unequally loaded or upon curves to prevent too great tilting of the car.

Lighting.—The very unsatisfactory nature of car lighting at the present time, especially upon interurban roads, has been commented upon in a previous chapter. The reason for this in the face of public criticism on roads where everything else is done for the convenience and comfort of the passengers is difficult to understand. The present method of lighting is that of using several series of five incandescent lamps each protected by fuses and connected directly between the trolley and ground so that the lights will not be extinguished when the circuit breaker opens. Several clusters are distributed throughout the hood of the car and often a light is placed over each seat. The incandescent headlight, if one be used, may be lighted in place of the vestibule light on the front end of the car by means of a snap switch. All the lights are, of course, dependent upon trolley voltage which has been previously shown to vary over a wide range with more than proportional variations in light intensity. A lighting system independent of trolley voltage must sooner or later replace this unsatisfactory method of car lighting.

Arc headlights are generally used on interurban lines with some provision for operation upon city streets such as a gauze shade, reduced voltage, polarity reversal in the case of the magnetite arc or the substitution of an incandescent lamp. These headlights require from 4 to 4 1/2 amperes at 550 volts, of which over 80 per cent. is wasted in external resistance.

Heating.—City cars and some of the smaller interurban cars are heated by means of electric heaters provided with switches

located in the vestibule which will permit several degrees of heat by changes of the heater coils from series to parallel grouping. The problem of car heating, especially upon long exposed runs at high speed in the coldest weather is a serious one, a car requiring from 10 to 30 amperes at 550 volts for such service. One large city railway system in particular, although able to supply the demands of summer traffic with existing power station equipment was forced to install additional apparatus and enlarge its station in order to meet the car heating demand in winter.

Interurban companies and especially those operating single-end cars have adopted the hot-water heating system almost

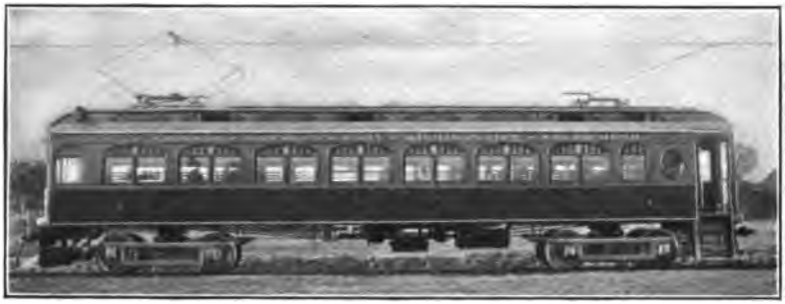


FIG. 85.

exclusively, the heater being located in one end of the car, preferably in the baggage compartment or motorman's cab. This system has the double advantage of low cost of operation and more even distribution of heat in the car, this being accomplished by means of pipes encircling the car near the floor as in the case of the cars of steam railroads.

Current Collection.—Little change has been made in the overhead trolley since the earliest days of electric traction, its operation being entirely satisfactory except for the very highest speeds or for the collection of very heavy currents. Large trolley wheels are used for high speed service and each road has a particular composition for the wheel casting which is believed to be best for local conditions. Wheels should run from 5,000 to 10,000 miles before replacement is necessary.

The pantograph bow collector is coming into general use in

high voltage high speed service. Such a device is illustrated upon a car in Fig. 85. It is raised to the wire by air pressure, the controlling valve being in the motorman's cab. With this type of collector the alignment of the trolley wire is not important, as the collector is often two or more feet in length and any transverse movement prevents local wearing of the collector.

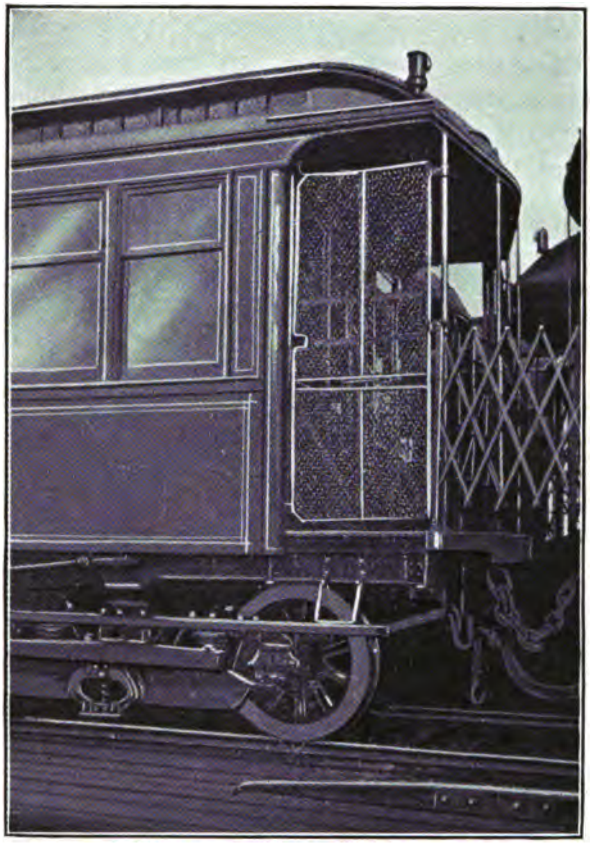


FIG. 86.

The third rail shoe for collecting heavy currents from the third rail mounted beside the running rails has been referred to previously. A view of one of the many types may be found in Fig. 86. Some difficulty has been encountered in the past with this construction in winter for if sleet be allowed to form on

the rail the shoe tends to ride on the sleet and a poor contact with much arcing results. Various methods have been devised to overcome this difficulty with more or less success. Those most used are a steel brush or scraper placed ahead of the shoe and sprinkling the third rail with brine.

Car Wiring.—A great deal of laxity has existed in the past in regard to car wiring and many accidents and fires have resulted in consequence. As the Underwriter's Code does not rigidly apply since cars are not insured, the tendency has been to use little care in running the wires under the car. Rubber covered wire is of course used, but it is customary to group all the wires together in one or two cables in a length of canvas hose hung from the car sills and extending from motors to controllers. The cable extending from the trolley base is supported on the top of the car roof by means of brass clips and is carried either into the car vestibule to the circuit breaker with only the insulation of the wire or, in the case of master control, it is carried down one of the corner posts of the car in moulding.

Recently the Fire Underwriters have drawn up a code of rules for car wiring and many improvements have resulted therefrom. Asbestos lined conduit is now often laid under the seats of the car for the installation of cables while in the best construction, used especially in subway cars, iron conduit is installed as in building wiring. Present practice also involves asbestos lumber or galvanized iron protection between wiring and wooden car frames, especially over the rheostats. Car wiring diagrams will be considered under "Types of Control," Chapter IV.

Special Types of Cars.—The above discussion applies to all types of cars. The special features of cars designed for a particular service will be outlined below.

City Cars.—In the smaller cities where traffic is not particularly heavy the 20 ft. single truck car with longitudinal seats is still used. The corresponding summer equipment would be a 20 ft., ten bench single truck car with running board. Officials differ as to the advisability of maintaining a double motor equipment and many of the smaller roads shift the equipment twice a year from one type of car to the other. With single trucks this involves considerable labor, but if double trucks be used the

trucks complete with motors can be changed with little trouble. Where summer traffic is heavy, especially to summer resorts, the 35 ft., 15 bench, double truck open cars or small trailer cars are used.

In the large cities the convertible or semi-convertible double truck cars, Fig. 87, with either transverse seats throughout or a combination of transverse and longitudinal seats are adopted, the same cars being used throughout the year. This avoids duplication of equipment and the dangers incident to the operation of the running board type of car in congested districts. Cars with transverse seats are much more comfortable, especially

FIG. 87.

for long rides, but they do not permit rapid ingress and egress, nor do they provide the standing room for a given size of car that the longitudinal seats furnish. The combination of both types of seats for long cars with the section of transverse seats in the center of the car permits the long-haul passengers to ride in comfort and yet furnishes more readily accessible seats and standing room for the local traffic.

Pay as You Enter Cars.—This type of car which has been quite recently adopted in the large cities with considerable success has the advantage that the conductor may always remain on the rear platform to start and stop the car promptly and to avoid possible accidents. The probability of obtaining all the fares when traffic is heavy is also increased. An apparent disadvan-

tage is the increased length of stop, but this has not proved to be serious as the platforms in this type of car are very large and when this platform is filled the car is started. The fares are

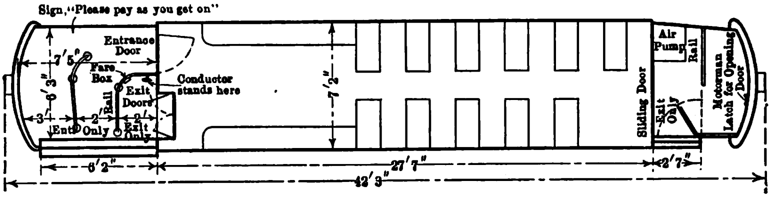


FIG. 88.

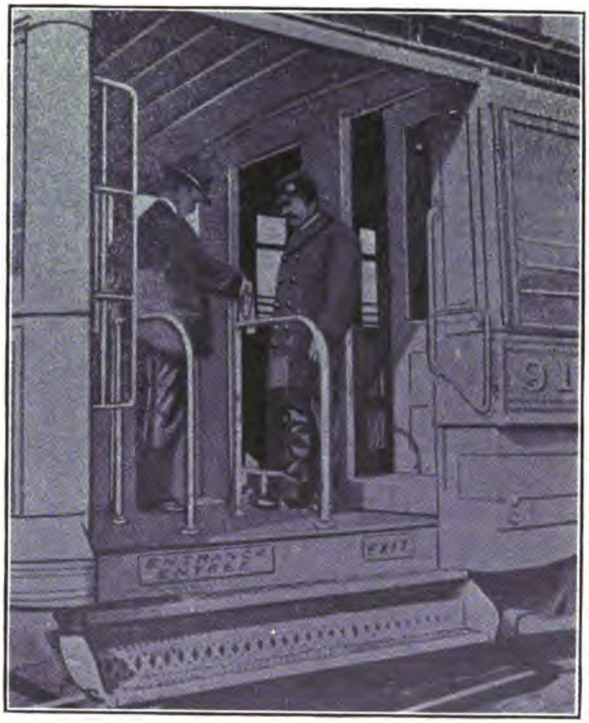


FIG. 89.

paid before the passengers enter the car, but during the period the car is in motion. This procedure, together with the time saved by the conductor being in a position to start the car promptly has permitted the same schedule to be maintained in

several cities with less cars where this type of car has been adopted. A plan view of this type of car will be found in Fig. 88, while the method of paying fare is well illustrated in Fig. 89. These cars are almost invariably designed for single end operation.

Suburban Cars.—This service in large cities is maintained with the semi-convertible car of the double truck type, in some

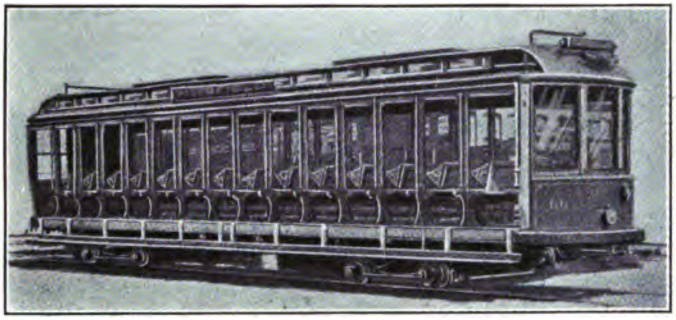


FIG. 90.

instances with the addition of vestibule doors operated by compressed air controlled by the motorman. With this equipment, the motorman is required to close all the doors of the car after the starting signal has been given, but before the car is started. In most installations of this type of car the car step is hinged and so connected with the doors that it is folded up as the door closes. This successfully prevents attempts to board cars when in motion.

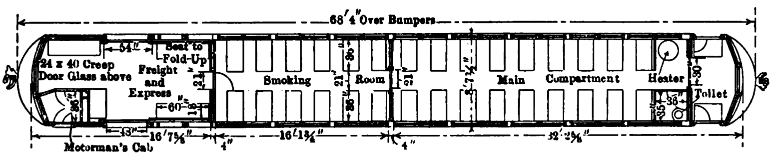


FIG. 91.

Open running board cars are used much more in the East than in the Middle West for suburban service. Such a car 42 ft. 6 in. in length and weighing 13 tons without electrical equipment is shown in Fig. 90.

Interurban Cars.—Cars which have been developed for interurban service which has recently grown so rapidly, particu-

larly in the Middle West, are patterned after the steam railroad coaches and often reach lengths of 68 ft. and weights of 50 tons. These cars are equipped with transverse seats and are divided into four compartments, for motorman's cab, baggage, smoking and main passenger service respectively. This design of course precludes double end operation. A plan view of such a car may be seen in Fig. 91, while a similar car designed as a sleeper and

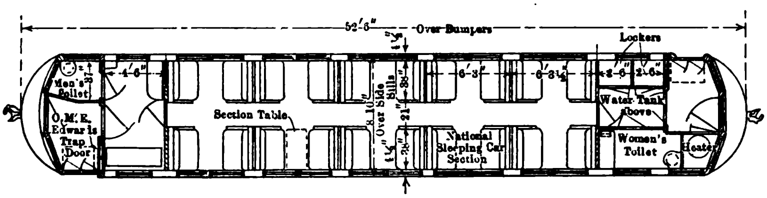


FIG. 92.

operated upon the Illinois Traction Company's lines between St. Louis and Peoria, Illinois, is illustrated in the plan view of Fig. 92.

Elevated and Subway Cars.—In the elevated and subway service in the largest cities a slightly different type of car is required, although it is patterned closely after the interurban car. Exits are so located as to be flush with the platform floors, no

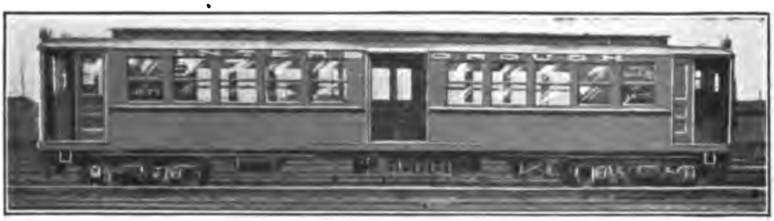


FIG. 93.

steps being necessary. In Boston and New York both side and end doors are provided and with the traveling public trained to enter by the end door and leave the car by the side door, some time is gained at the station. Both transverse and longitudinal seats are provided. These cars are designed to operate in trains, each train consisting of both motor cars and trailers, all motor cars being operated by means of the multiple-unit control from the

motorman's cab of the forward car. In the New York subway steel cars are now being adopted, one of this type being illustrated in Fig. 93.

While the life of cars will vary from ten to twenty years, depending upon the type, severity of service and the attention which they receive in the shops, obsolescence has been the reason for discarding most of the cars used thus far, *i.e.*, traffic demand has required that larger and better cars replace those in operation before the latter were actually worn out.

CHAPTER III.

MOTORS.

Much of the theory underlying the operation of the direct current series motor has been discussed in a previous chapter. A brief outline of their construction and selection together with the principle of operation of the alternating current motors used in railway systems will be herein considered.

Direct Current Motor.—The direct current series railway motor, Fig. 94, differs from the stationary type principally in the design of the frame, that of the former motor consisting of a box-like iron casting split in a plane through the center of the shaft

FIG. 94.

and hinged in such a manner that the lower half of the frame with two field poles and windings may be lowered for inspection of the armature with the motor in place on the truck. The larger motors are of the so-called "box" type with the frame in a single casting. The armature is removed from this motor by taking off the end bearing plate and drawing the armature out in a direction parallel with the shaft through the opening thus made. The motor must be removed from the truck for this operation. The frames of both types of motors are provided with openings and

moisture-proof cover plates for ready access to armature, commutator and connecting cables. These cables are brought out through insulating bushings in the frame of the motor, which are usually located on the side next to the truck bolster, in order that the movement of these cables may be least when rounding curves.

Railway motors are generally of the four pole type with the axes of the poles at an angle of 45° with the horizontal in the split frame types. Field coils are wound with rubber or asbestos covered wire with asbestos insulation between layers or in the larger motors with copper strip. The coils are taped, impregnated with insulating compound with the vacuum process and waterproofed.

Two sets of bearings are provided in the frame, one pair for the car axles and the second for the armature shaft. These are of babbit lined cast bronze.

The armature and commutator are not unlike those of stationary motors except that the armature is series wound and requires but two sets of brushes. These are placed on the top portion of the commutator and are therefore accessible through trap doors in the floor of the car. The brush holders are fixed in position and support the carbon brushes in a radial position on the commutator so that the motor may operate equally well in either direction.

Commutating Pole Motors.—As in the case of direct current stationary motors and generators, the rather marked advantages of the commutating pole are applied to the railway motor. These commutating poles are auxiliary poles provided with a winding connected in series with the armature. As the magnetic flux in these poles will vary with the armature current the serious effects of armature reaction upon commutation are neutralized at all loads by the flux from these auxiliary poles. The latter are so designed and located that the short circuit current in the coil under the brush is small and sparking at the brushes therefore a minimum. As the output of the motor is often limited by commutation as well as temperature rise, the overload capacity will be increased and its maintenance cost reduced. It is claimed that 100 per cent. overload may be suddenly thrown on and off such a motor without sparking at the brushes.

Single Phase Motors.—With the increase in length of interurban lines and their large power demands together with the realization of the high first cost and maintenance charges on the converting equipment necessary for long direct current roads, came the serious study of the possibilities of alternating current motors for railway use. It was at once recognized that if a satisfactory alternating current railway motor could be developed considerable saving could be made in the above factors and a marked simplification in the distribution system effected, as pointed out in the chapter on the distribution system, to say nothing of the possible reduction in distribution system losses due to the increase in trolley voltage. As the polyphase motors which have been developed were of the constant speed type with inherent characteristics unfavorable for traction and since the advantages of polyphase transmission at high voltage can be gained without the complication of a polyphase distribution system and car circuits, the attention of American engineers was first turned to the development of the single-phase motor for traction purposes.

This development may be approached either by endeavoring to adapt the direct current series motor, whose characteristics have proved satisfactory for traction purposes, for use upon single-phase alternating current circuits or the alternating current induction motor may be studied with a view toward redesigning it for railway use. Both of these viewpoints will be considered in the order mentioned.

Adaptation of the Direct Current Series Motor.—Those familiar with the direct current motor will remember that a reversal of the current in either armature or field alone will reverse the direction of rotation of the motor, whereas a reversal of both field and armature connections will not change its direction of rotation. It might be predicted therefore that when a direct current series motor is connected to an alternating current circuit of proper voltage, the motor would operate. This was found to be the case, although many effects of the alternating current, which are discussed below, cause the motor to operate unsatisfactorily from a practical standpoint unless several changes are made in its design.

The e. m. f. impressed upon a direct current series motor is balanced by the sum of counter e. m. f. of revolution (E_r) and the (IR) fall of potential in field and armature windings. In addition to these there exists in the series motor operating upon an alternating current circuit the reactive voltage of the series field and armature windings.

The reactive voltages are due to the self induction of the respective windings or better to the cutting of the conductors by the lines of leakage magnetic force which encircle one set of conductors only and are therefore not useful in producing counter or

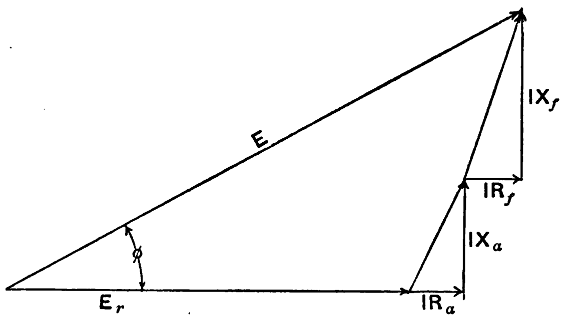


FIG. 95.

energy electromotive force. This voltage is 90° in advance of the current and may be treated as though there were an external choke coil of corresponding reactance connected in series with the motor. It is directly proportional to the frequency of the voltage supply.

With these voltages in mind the vector diagram of the motor may be drawn as in Fig. 95 where

- E = Impressed voltage.
- E_r = Counter e. m. f. of revolution.
- I = Current in armature and field.
- R_a = Resistance of armature.
- X_a = Reactance of armature.
- R_f = Resistance of field.
- X_f = Reactance of field.
- ϕ = Angle between impressed voltage and current whose cosine is the power factor of the motor.

From the diagram it will be seen that any change of design that will reduce (X_f) and (X_a) will increase the power factor of the motor. This is a desirable change as a higher power factor results in smaller losses and higher torque in the motor not only, but either lower losses or less copper in the distribution system as well. The reactance voltage of the armature (IX_a) may be more or less completely neutralized by means of a compensating winding which will be subsequently explained, while that of the field can only be reduced by reducing the turns on the field or the magnetic induction.

Before these possible changes are studied further the question of commutation may well be investigated, for the commutation of a direct current motor operating upon alternating current is noticeably poor. It will be remembered that in the commutation of direct current motors, care must be taken to have the current a minimum in the coil or coils which are short circuited by the brushes in order that the spark which occurs when the coil is disconnected from the brush by the movement of the commutator may not be serious. Reference to Fig. 96 will show, however, that there is an additional factor to be considered in the commutation of an alternating current motor. The motor is quite similar to a transformer in that it has a magnetic circuit surrounded by two sets of coils, the field and the armature. The pulsating flux set up by the field generates an electromotive force due to this transformer action in the coils of the armature, those coils in the plane (a′b′) which enclose the greatest number of

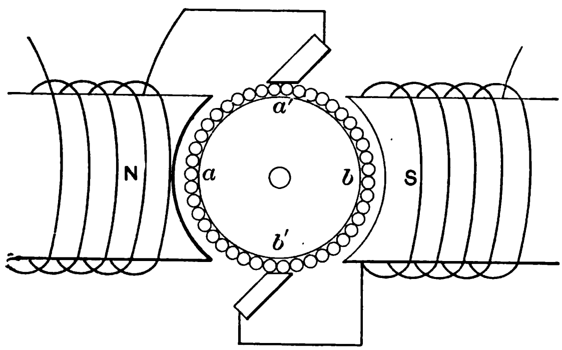


FIG. 96.

magnetic lines of force generating the highest voltage and those in the plane (ab) theoretically zero voltage. But one or more of the coils in plane (a′b′) are short circuited by the brushes. A large current flows through this coil therefore as in the case of a short circuited secondary coil on a transformer. Unless the design is altered so as to reduce this current, vicious sparking will take place and seriously limit the commutating capacity of the motor.

Two methods of reducing this short circuit current are in general use. One makes use of an auxiliary coil placed 90 electrical degrees from the field coils as in the case of the commutating poles on direct current motors. This so-called "compensating" coil is in series with the armature and is designed of such strength as to neutralize the combined effect of transformer e. m. f. and armature reactance e. m. f. While such a coil can be made to perform such neutralization for one load and partially neutralize the e. m. f. on all loads, its effect is not complete over the entire range of load, it being particularly faulty at very light loads. One of the large manufacturing companies overcomes this light load fault by inserting "preventive" leads between the point where connection is made between armature coils and the commutator. These leads are of relatively high resistance and therefore tend to limit the short circuit current to a minimum. As the current circulating through the armature coils encounters the resistance of the preventive leads only as it flows into or out from a brush, the heat loss in the leads is not large. The combination of compensating coils and preventive leads not only puts the commutation of the alternating current series motor on a par with that of the direct current motor, but it increases the power factor to a practical operative value as well.

Returning to the question of reducing the reactance e. m. f. of the field in order that the power factor may be still further increased. If this be done by reducing the field flux, the capacity of the motor is correspondingly lowered. It is actually accomplished in practice, therefore, by reducing the number of field turns to from 20 to 25 per cent. of those in a direct current motor of similar characteristics. This is rather difficult with the large capacity motors having a relatively large number of poles.

Aside from the above changes in design which are necessary in order to adapt the direct current motor to use with alternating current, the field must be laminated as well as the armature to prevent serious eddy current losses. The reluctance of the magnetic circuit must be reduced in order that the flux may not be sacrificed with a smaller number of field turns and joints are therefore eliminated and the sectional area of the poles increased. Theoretically the length of the air gap might be shortened to produce the desired reduction in reluctance, but this is not considered advisable from a practical operating standpoint, for with the direct current motors the bearings often wear to such an extent that the armature rubs on the lower field poles.

Adaptation of Induction Motor.—The evolution of the single phase induction motor into the alternating current series railway motor has been very clearly explained from the theoretical standpoint by McAllister.[1] Briefly the development is as follows: Suppose a single-phase induction motor stator to be provided with an armature similar to that of a direct current series motor and the stator and armature windings to be connected in series. McAllister shows very clearly that with all possible ratios of field to armature turns the power factor will not exceed 45 per cent. and the maximum limit of the ratio of starting to synchronous torque will be in the neighborhood of 125 per cent. Both of these values are too small for a satisfactory railway motor.

If the reluctance of the air gap between polar regions be increased by forming polar projections in the stator fields such that the ratio of reluctance of the leakage path between poles to that under the poles may be considered as infinite, the power factor and torque ratio may be increased over a wide range by properly proportioning the armature and field turns. The successful railway motor may be considered, therefore, as an induction motor stator with projecting poles enclosing an armature similar in design to that of a direct current series motor.

Construction of the Single-phase Motor.—As the result of the above studies a motor has been developed which is giving very satisfactory results upon single-phase railway systems of

[1] Alternating Current Motors by McAllister.

low frequency (25 cycles) especially in the larger sizes which have been applied to locomotives.

Such a motor, Fig. 97, does not appear materially different from the direct current motor, consisting of a cast steel box type frame supporting the laminated iron stator which is so punched as to form polar projections. These are, however, shorter than in the direct current motor. The motors are provided with four or six poles and their field windings are of the distributed type similar to those of the single-phase induction motor. The wind-

FIG. 97.

ing is of heavy strap copper, however, and consists of a relatively few turns. Between the main field windings are located the compensating windings connected in series with the armature. The armature is practically identical with that of the direct current motor with the exception that because of the lower voltage and consequently higher current for which it is designed it is usually necessary to provide one set of brushes for each pole.

Characteristics.—The characteristics of the single-phase motor are strikingly similar to those of its competitor, as will be seen by comparing Figs. 98 and 13. The efficiency of the former motor is slightly lower and the torque-current curve slightly more

concave owing to the lower induction for which the alternating current motor is designed. With the fields unsaturated, therefore, the torque will vary with the square of the current.

Operation on Direct Current.—One of the most important features to commend the single-phase series motor as above described is its satisfactory operation on direct current circuits. If the changes which have been made to adapt the motor to alter-

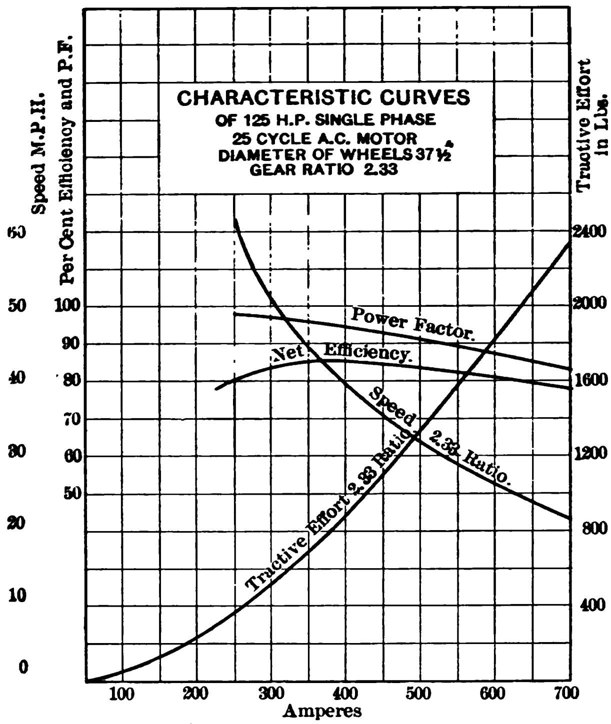


FIG. 98.

nating current are reviewed it will be noted that no change made impairs its use with direct current. Since it is highly important that interurban roads operate their cars to the center of the terminal cities over the existing direct current trolley, this feature of the series alternating current motor is of greatest value. Whereas the control system must be duplicated to some extent, as will be seen in the next chapter, the flexibility of operation is well worthy of the slightly added complication.

Repulsion Motor.[1]—When it was found that a corrective current could be made to flow in the armature of an alternating current armature by means of induction between windings as in the case of the transformer, it was inferred that such a current might be made to produce a torque without connection between armature and field as in Fig. 99. Such a motor was found to

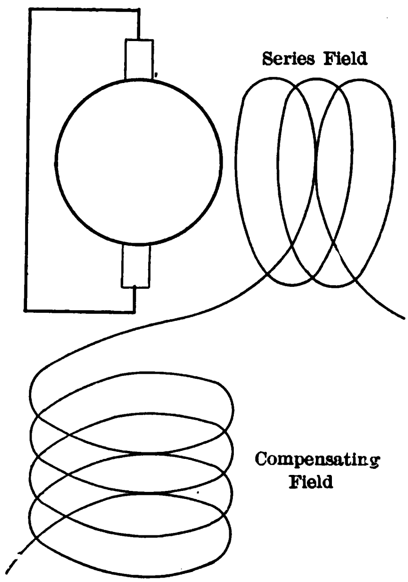


FIG. 99.

operate satisfactorily, the brushes being short circuited to allow the torque producing currents to flow in the armature windings. The characteristics of such a motor are similar to those of the series motor. This motor has been designated as the repulsion motor. Although it was expected that it would find a ready application in the railway field it has not come into use largely because of its inability to operate upon direct current systems and the additional fact that it apparently has no marked advantages over the series motor.

[1] The Alternating Current Railway Motor by C. P. Steinmetz, A. I. E. E., Vol. XXIII.

Speed Torque Characteristics of the Single-phase Repulsion Motor by Walter I. Slichter, A. I. E. E., Vol. XXIII.

Alternating Current Motors by McAllister.

Induction Motor.—The induction motor has characteristics similar to those of the shunt direct current motor and is, therefore, generally unfit for railway service. It may be designed, however, for several different speeds, usually by placing a winding upon the rotor and varying the resistance in the rotor circuit or in some cases by the so-called concatenation method in which the stator of one motor is supplied from the rotor circuit of a second motor. With these adaptations this motor has been considerably used abroad for railway service and in one installation in this country, upon the Great Northern Railway[1] where the requirements seemed to be particularly well filled by a motor of constant speed characteristics.

Frequency.—The question of frequency has not been directly referred to in the above discussion. If reference be made again to the factors which were necessarily changed in the direct current motor to adapt it to alternating current operation it will be noted that these factors, principally reactance voltages, are reduced by reduced frequency. The lower the frequency, therefore, the easier it becomes to design a satisfactory alternating current railway motor and the greater the capacity which it is possible to obtain with a given size and weight of frame and, therefore, the greater the capacity that can be supplied to a single truck or to a single pair of driving wheels.

Rating.—Railway motors, because of their rather intermittent service at varying loads with a greater amount of ventilation in actual use than upon the testing floor, are rated differently than other electrical machinery.

A motor is said to be of a certain capacity expressed in horse power if it will delvelop such a horse power continuously for 1 hr. with a temperature rise of 75° C. above the room temperature corrected to 25° C. when operating with the openings in the motor frame uncovered. This represents a rather arbitrary rating, but offers a basis for the comparison of motors.

Motor Selection.—The method of determining the total power required to operate the car has been explained in a previous chapter. After the number of motors per car has been decided

[1] The Electric System of the Great Northern Railway Company at Cascade Tunnel by Cary T. Hutchinson, A. I. E. E., Vol. XXVIII.

upon as outlined in the last chapter, the capacity of the motors to be installed may be approximately determined by dividing the average car demand expressed in horse power for the various runs by the number of motors per car. If care be taken not to load the motor continuously with its rated load and still make due allowance for its overload capacity for short intervals and the extra demands of abnormal service, this method should permit a correct selection of the nearest standard motor to be made.

Several other methods of making this selection may be adopted, however, and it is always well to check the motor capacity chosen by two or more processes. They will be briefly explained in order of their ease of application.

Selection by Comparison.—A very rough and simple method quite commonly used is to prepare a table from technical journals or the railway census of the equipments of various roads operating under as nearly as possible the same conditions as the proposed road. This table should include number and capacity of motors, average voltage, schedule speed, weight of cars, layover at terminals, stops per mile, average grade and if possible the watt hours per ton mile demanded. By comparison with such a table the correct standard size of motor for the new equipment may readily be determined.

Effective Current Method.—It is possible to obtain from manufacturers' test records not only the rating of the motor, but also its continuous current capacity at one or more average voltages, *i.e.*, the current which may be supplied to the motor continuously without exceeding the limit of 75° C. temperature rise. The temperature curves of Fig. 13 may also be obtained from which the time required to rise to 75° C. above the room temperature from the start with the motor cold can be found for each value of current supplied to the motor, as well as the time required to rise 20° above 75° C. for the various possible over-load currents. In making use of these data it should be remembered that the heating of a motor is proportional to the square of the current. The heating value of the current or "effective" current for a given run is not the average ordinate of the current-time curve of that run, but the square root of the average squared current. If then the effective current for the various runs as determined

from the current-time curves be compared with the continuous current rating of the motors with due allowance for temperature rise of short duration produced by overload currents as determined from the temperature curve, the proper motor may be readily selected. In short, a temperature time curve is really determined for the various runs and the motor so selected that this curve will not exceed 75° C. rise for other than short intervals of time.

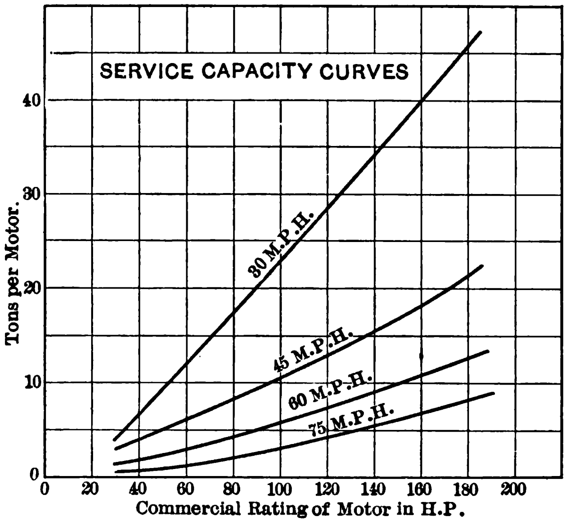


FIG. 100.

Method Proposed by Armstrong.—In a paper before the American Institute of Electrical Engineers[1] Armstrong suggests that a series of curves such as Fig. 100, each representing the motor capacity required for a given weight of car per motor and for a certain speed, acceleration, etc., be prepared from theoretical and practical test data and used for quick approximations of motor capacity. Fig. 100 is plotted for straight level track with the following assumed values:

Gross accelerating force, 120 lbs., per ton.

Braking decelerating force, 120 lbs. per ton.

Duration of stops, 15 seconds.

Duration of coasting, 10 seconds.

[1] High Speed Electric Railway Problems by A. H. Armstrong, A. I. E. E., Vol. XXII.

Since this data does not take into consideration grades and curvature or other values of acceleration, deceleration, etc., than those listed, either a large number of such charts must be plotted or the results taken from same carefully corrected for any variation of actual from assumed conditions.

Method Proposed by Storer.[1]—This method assumes that a certain motor has been tentatively selected and that it is desired to determine from test under conditions similar to those of actual service whether or not this particular motor will fulfill the requirements.

The effective current for the various runs is determined as explained above and the average voltage at the terminals of the motor found from the voltage time curve. If, now, the motor be operated with this effective current and with the average voltage impressed upon it, the motor losses will be the same as in practice and the heating of the motor under service conditions may be determined therefrom. It should be remembered, however, that the ventilation of the motor is better in service and it may usually be depended upon to carry from 20 to 25 per cent. more load with the same temperature rise when on the car. This allows a good factor of safety if the motor be selected from test results.

Method Proposed by Hutchinson.[2]—The method employed by Hutchinson where a large number of motor determinations are to be made by a manufacturing or an engineering company is one involving mathematical equations based upon a large number of general charts deduced from the typical speed time curves. In place of assuming the straight line speed time curve of Part I, Chapter X, to be correct, a mathematical correction applying to the difference in area between the accurate and the straight line speed time curve is used and constants derived which, when substituted in the equations given, enable the latter to be solved for correct motor capacity. For further details reference should be made to the original paper.

[1] By N. W. Storer, Street Railway Journal, 1901.
[2] A. I. E. E., Vol. XXI.

CHAPTER IV.

TYPES OF CONTROL.

The necessity of starting a car by first impressing a low voltage upon its motors and then gradually increasing the voltage as the motors speed up until they are receiving their rated voltage, has been previously explained. The advisability of maintaining a constant current through each motor during the constant acceleration period was also pointed out. It is now necessary to consider the various standard control systems which have been devised to accomplish the above results.

Rheostatic Control.—The earliest type of control, which is now practically obsolete, made use of a rheostat in series with the motors, but did not change the motor connections from start to full speed. Two complete revolutions of the controller handle were necessary to cut out all the resistance, but the rheostat was so designed that the controller handle could be left in any position indefinitely and correspondingly small variations of speed obtained.

Series Parallel Control.—Practically all the control systems in use with direct current railway motors at the present time, although differing widely in detail, operate upon the series parallel principle. The two motors of a two motor equipment or those of each group of a four motor equipment are first connected in series with one another and also in series with a resistance. This resistance is then reduced by three or four steps until the two motors are alone in series across the circuit from trolley to ground. This notch of the controller is termed a "running" notch as the controller may be left in this position continuously, resulting in about half speed. With the next step, the motors are changed from series to parallel connection and a resistance again introduced. This resistance is reduced in the succeeding steps until upon the last notch all motors are in parallel without resistance. This is ordinarily the full speed position, although in some types of this control an additional step is employed which shunts the motor

field with a resistance and thus increases the speed still further. A K-12 controller, which is commonly found on city cars with four motor equipments is shown diagrammatically with motor and resistance connections in Fig. 101. The connections for the various notches may be readily traced if the heavy black horizontal bands representing the copper sectors on the control cylinder

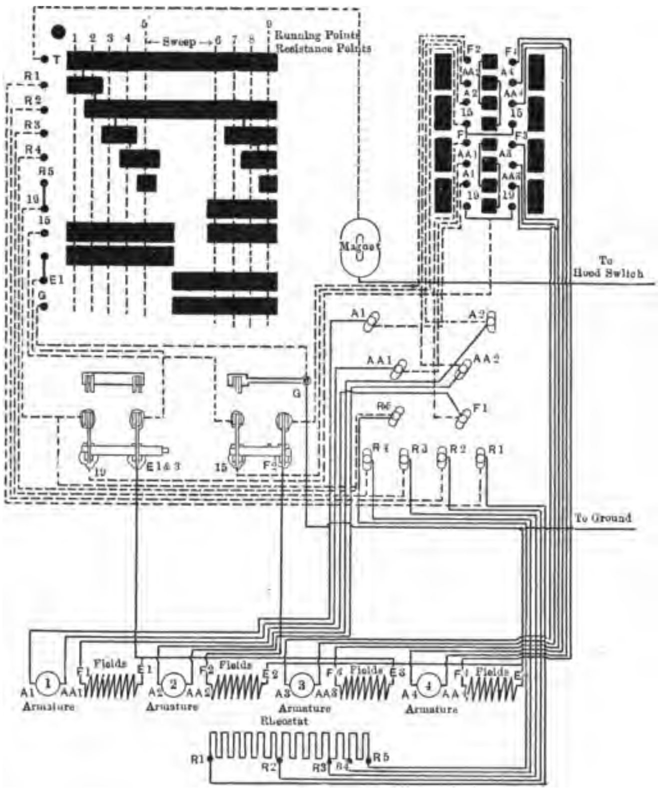


FIG. 101.—K-12 Wiring Diagram.

be assumed to move one numbered notch to the left for each change of connections. Care should be taken to trace out the reversal of armature connections as the reverse cylinder represented by the heavy bands at the right of the figure is turned. The switches numbered (19) and (15) are used in cutting out one set of motors in case of their failure. The resistance steps are so

proportioned that if the controller is steadily "notched up" an approximately constant current will be maintained through each motor. A diagrammatic illustration of the various steps is found in Fig. 102. As may have been inferred from the above discussion, the resistances are designed to remain in the circuit for a

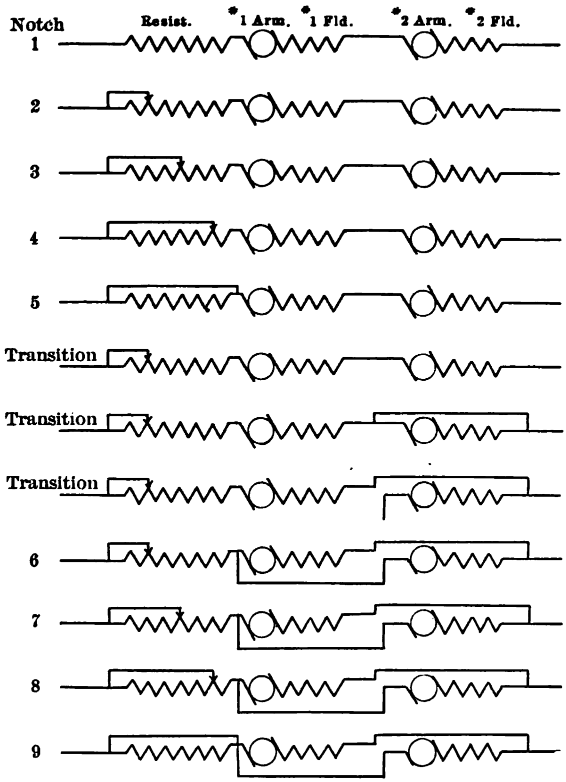


FIG. 102.

short time only and will therefore overheat if they be left in circuit continuously.

The mechanical construction of the series-parallel controller may be noted from Fig. 103 which shows the interior of a K-11 controller with asbestos barrier opened. This particular controller has been provided with additional barriers by the operating company to prevent arcing between contacts. The main

drum with its copper sectors insulated from the shaft and engaging copper contact fingers will be seen on the left and the reverse cylinder of similar design on the right with the blow-out magnet below. A sufficient flux is produced in this magnet to blow out the arc which is formed between the various fingers and sectors as the circuits are opened. At the bottom will be found the motor cut-out switches and the connection board.

In order to prevent the current through the motors from being increased too rapidly two different methods are used. A mechanical device may be attached to the top of the controller which

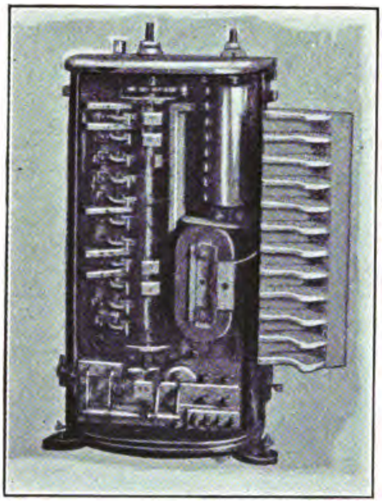


FIG. 103.—K-11 Controller.

by means of a ratchet and pawl prevents the forward movement of the controller handle in a single swing, but requires a slight backward movement at each notch to disengage the pawl and thereby allow sufficient time for the current to decrease to its normal accelerating value. The second method involves the use of a specially designed controller with a limit relay through which the motor current passes. Although the handle may be thrown completely around in a single swing, this movement simply puts a coiled spring in tension which "notches up" the controller as fast as the interlocking relay will permit. When the current falls to a predetermined value on each step the relay unlocks the con-

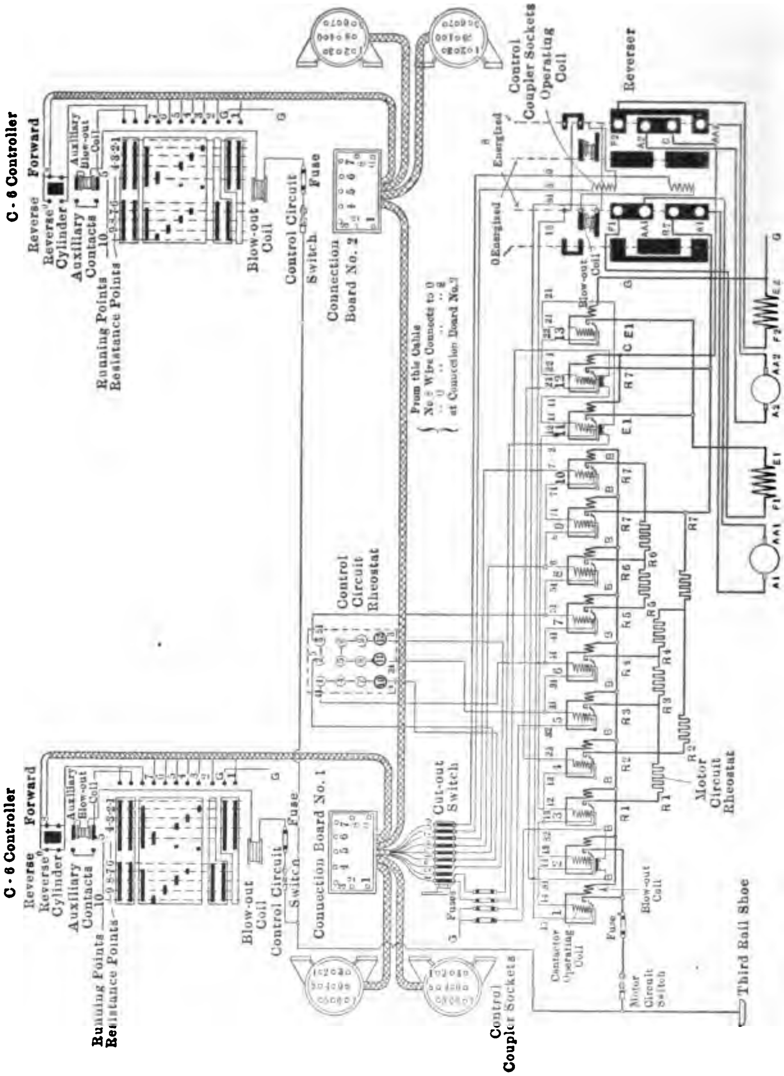


FIG. 104.—Wiring Diagram, Multiple Unit Control.

troller spindle and allows it to progress to the next step automatically.

Master Control.—With the rapid increase in the current required by the motors as the size and capacity of electric railway equipment advanced, it became more and more difficult to design a controller of the type described above to continually break these large currents. As a result a master controller is often found in the motorman's cab, quite similar in principle to the large con-

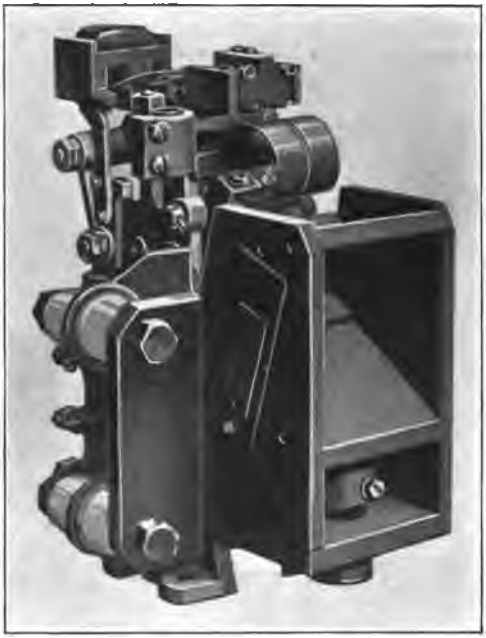


FIG. 105.—Contactor.

trollers, but designed to control an auxiliary circuit only. This auxiliary circuit operates a series of contactors or solenoid operated main switches mounted under the car. With such a system the contactors may be sufficiently large to control the heavy currents safely and little room is required for equipment above the floor, not to mention the reduction in the amount of heavy cable demanded by such an equipment. The auxiliary circuit may be a high resistance circuit supplied from the trolley or in some instances it is supplied by a storage battery of about 14 volts.

Multiple Unit Control.—There is a demand in elevated, subway and heavy interurban service for the operation of a number of cars in a single train from the motorman's cab of the front car. A marked advance in the design of control equipment was made, therefore, when the multiple unit control system was developed by Sprague. This system embodies the use of the master controller explained above not only, but it permits the contactors upon all cars to be operated simultaneously by the master controller of a single car, the small auxiliary circuit wires alone extending between cars through the agency of flexible cables and plug contacts. The equipments are all interchangeable so that any car

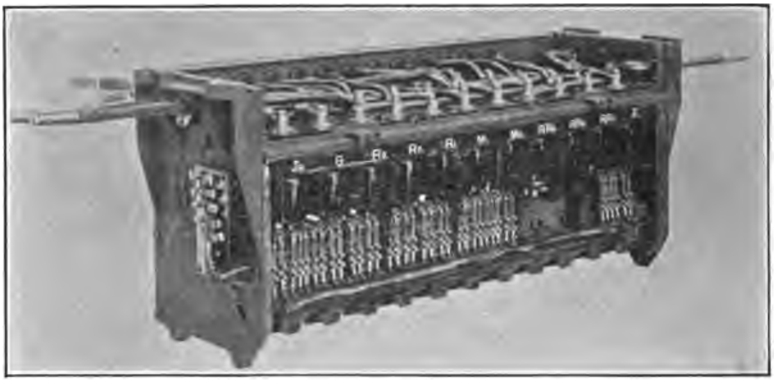


FIG. 106.—Unit Switch Group.

may be made a control car. Fig. 104 represents the wiring diagram of both the main and auxiliary circuits of the multiple unit control in detail, while Fig. 105 illustrates the contactor with its relay contacts at the bottom and its asbestos trough for the circuit breaker at the top.

Unit Switch Control.—The unit switch control is a system developed by another manufacturing company to meet the requirements of master control of single car equipment or of multiple unit control. In fact upon one large railway system cars with the unit switch control and the Sprague multiple unit control are operating interchangeably in the same train.

The unit switch control differs from the Sprague multiple unit system principally in details of operation, the principle of the two

being the same. Both systems have the main switches and reversers located under the car, the operation of these switches being controlled by the master controller and an auxiliary or relay circuit. The unit switch system obtains its energy for the auxiliary circuit from one of two 14-volt storage batteries carried on

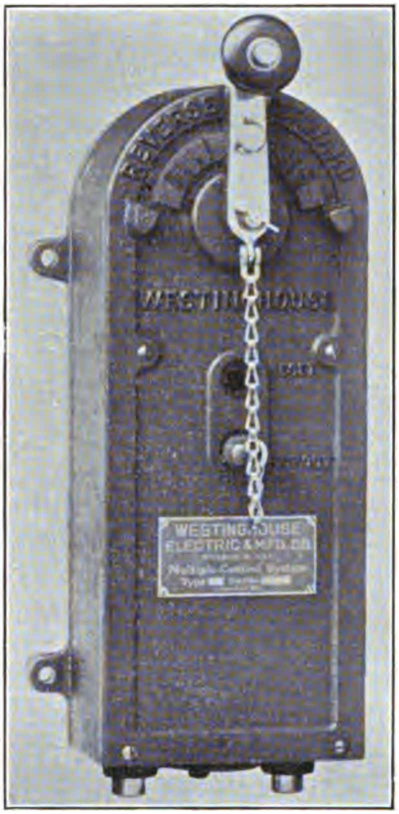


FIG. 107.—Unit Switch Master Controller.

the car, while the control circuit of the multiple unit system is supplied from the trolley. In the former system the main switches, Fig. 106, are operated by air pressure obtained from the main air brake reservoir, the air valves being operated by the battery circuit.

The automatic "notching up" feature of the unit switch system, which may also be secured with the Sprague multiple unit

control is accomplished by providing the main switches or contactors with relay contacts which make the proper connections in the auxiliary circuit as they open or close.

The master controller of the unit switch system, Fig. 107, is provided with three forward and three reverse notches, the function of which will be more clearly seen by referring to Fig. 108,

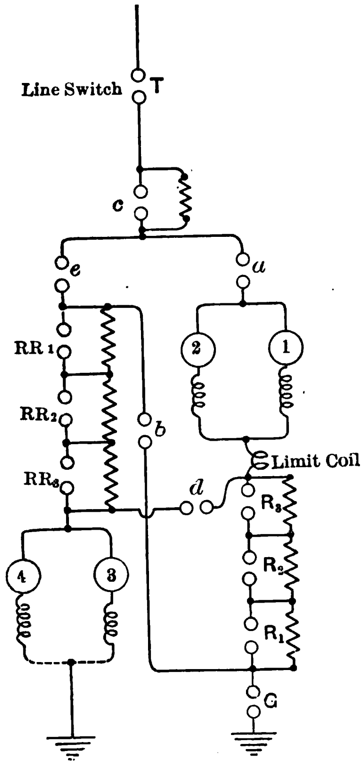
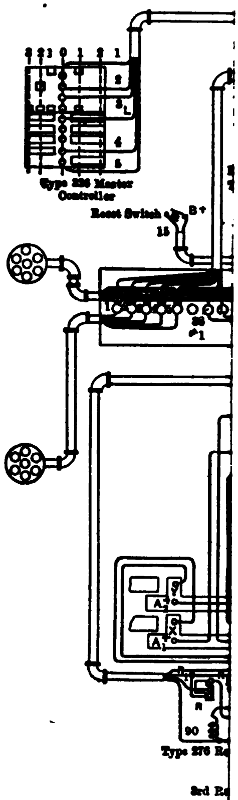


FIG. 108.

which is a much simplified connection diagram. The first notch closes the line switch (T) and the unit switches (a) and (b), thus putting the motors in series with all resistance in circuit. This is not a permanent running notch, but the train may be thus operated at slow speed for switching, etc., for a short time.

The second notch on the controller is the full series running position. This closes switch (C) which has interlocking contacts


Type 226 Master Controller
Reset Switch
B+
15
90

which in turn close (RR_1). The latter switch carries interlocks which close (R_1) and so on closing (RR_2), (R_2), (RR_3), (R_3), etc., in order, cutting out corresponding resistance steps until the motors are in series without resistance between trolley and ground.

Notch No. 3 or the full parallel running position closes switch (d) which in turn breaks the auxiliary circuit of (b) and the latter switch opens together with all the resistance switches except (c). When (b) has completely opened it causes switches (e) and (G) to close. When these are fully closed their interlocking relays open switch (d). When (d) is again open the circuits through the resistance switches (RR_1), (R_1), (RR_2), etc., are closed consecutively until the resistance has again been gradually cut out and the motors are finally operating in parallel across the line with no resistance. Limit relay switches described above prevent the resistance switches from closing before the current has decreased to its normal accelerating value. This maintains nearly constant current during the acceleration period.

In some forms of this control the handle of the master controller is automatically returned to the "off" position if the motorman takes his hand from same. This is arranged not only to shut off the current, but also to apply the air brakes automatically. With this design an additional coasting notch is introduced next to the "off" position for which the current is off, but the brakes are not applied.

A complete wiring diagram for the unit switch automatic multiple unit control system including both auxiliary and main circuits will be found in Fig. 109, but because of its complication the simplified diagram of Fig. 108 will be found preferable for all but detail connections.

It must be remembered that in all multiple unit control systems the power circuit of each car is complete in itself, with independent contacts with trolley or third rail. Each car, therefore, must have its own limit switch which may be adjusted for a different value of current for each car to correspond with the equipment upon that particular car. Provision is also made for all the switches to open on any one car in case of failure of power on that particular car, the switches "notching up" automatically when the power is again supplied. The latter feature is important with

third rail operation in which the power is off when passing over each crossing.

Alternating Current Control.—As the principal advantage in the use of alternating current motors on the car is the possibility of using high trolley voltages and as the alternating current motors are best designed for low voltage, *i.e.*, from 200 to 225 volts, a transformer must be used on the car to reduce the trolley voltage to that suitable for the motors. Since taps may be taken from the various coils of this auto-transformer to furnish still lower voltages useful in starting the car without the resistance loss entailed by the resistance type of direct current motor control the principle of alternating motor control differs somewhat from those previously explained.

Alternating current control systems may be either hand operated or of the master control multiple unit type. If the former, the controller is similar to the (K) series parallel drum controller with the exception that there are fewer notches, usually five or six only, and no series parallel connections. The magnetic blowout coil is also omitted as the alternating current arc is not difficult to extinguish without the coil. The various contacts made between controller sectors and the stationary fingers serve to connect the motors, generally permanently connected two in series, to the various taps of the auto-transformer. The reversal of the motors is accomplished in the same manner, the reverse cylinder reversing either the armature or field connections.

With the master alternating current control the principle of operation is the same as before. The magnetic cores of the reverser and contactors must, however, be laminated for use on alternating current circuits.

In order that connections may be changed from one transformer tap to another without opening the circuit it is necessary to close a local circuit through a portion of the transformer winding, *i.e.*, if special precautions are not taken a short circuit will be formed in a portion of the transformer coil as two taps of the transformers are connected to the same motor terminal. In order to avoid this difficulty the current is reduced in the local circuit by means of "preventive" resistance or reactance leads as in the case of the single-phase motor.

The auto-transformers used with the alternating current motor equipments have been standardized for 3000, 6000, and 10,000 volts trolley potential and are connected directly between trolley and ground, the motor leads being connected to taps near the grounded side of the transformer. The transformer is of the oil cooled type and is mounted under the floor frame of the car.

Combined Alternating and Direct Current Control.—As previously pointed out it is desirable that most alternating current interurban roads operate cars to the heart of the terminal cities. They must, therefore, be able to operate upon both alternating and direct current. In order that the control equipment may be fitted for either system some changes in detail must be made and a considerable complication of circuits results. The various parts of the apparatus such as controller, reverser, contactors, etc., are used in common by the two systems. A number of changes in connections, however, must be made in shifting from one system to another. These are principally as follows when changing from alternating to direct current operation:

Change transformer taps to resistance taps.

Change main fuses or circuit breakers.

Change lightning arresters.

Introduce the magnetic blow out into the circuit.

Change lighting and heating circuits.

Reconnect fields of air compressor motor for series operation. In order that these changes may be made in one operation the cables involved are connected to a second control drum similar to the main controller. This is styled the "commutating switch," the above changes being made by a simple movement of the handle. This change may also be made automatically at full speed by providing a release for the switch when no potential is supplied so that it will open as the car reaches an insulated section in the trolley between the alternating and direct current systems. The switch is designed to reset automatically in the opposite direction as the direct current trolley is reached and *vice versa*.

As may be inferred from the above an added complication enters into the problem in operating the air compressor for the air brake system. In some installations a motor generator set of small capacity is installed to furnish 550 volts direct current when

supplied with alternating current from the transformer. The standard direct current air compressor may then be used. Another method more often found is to design the compressor motor for both alternating and direct current, connecting the field coils in parallel for the former supply and in series for the latter.

Whereas the combination of the two control systems upon one car adds considerable complication, as will be seen from Fig. 110, which represents the complete wiring diagram for an alternating current-direct current control equipment, and although the first cost and maintenance charges are necessarily increased thereby the added advantages of alternating current operation apparently warrant such an installation, for several roads are successfully operating such an equipment.

CHAPTER V.

BRAKES.

The problem of stopping a car is quite as important as that of acceleration. Since the kinetic energy of the car must be overcome in a very few seconds the power required for braking the car is usually many times that required for accelerating. Whereas the rate of deceleration and energy required during the braking period have been already considered, it is now necessary to study the braking forces more in detail as well as the various types of equipment which have been designed for the production and control of such braking forces.

Electric cars must be accelerated and retarded by virtue of the frictional force between the wheels and the rails. As this force is proportional to the weight on the wheels, the available force is conveniently found from the ratio of horizontal pull in pounds necessary to slide the wheels on the rails to the pressure between wheels and rails. This ratio is commonly termed the coefficient of friction. It has been found to vary with the materials in contact, and the velocity and the length of time during which the force is applied.

While many different devices have been tried out in practice for producing the necessary frictional forces to stop a car, the one which is now almost universally used in both electric and steam railroad service is the application of a brake shoe, usually of cast iron or a combination of cast iron and other materials, to the treads and flanges of the car wheels by means of either hand or air pressure transmitted through the agency of a carefully proportioned system of levers.

Coefficient of Friction.—An experimental study of the cœfficient of friction between cast iron brake shoes and steel wheels under practical service conditions was made by Galton and Westinghouse in 1878, and the results of these tests, published in the 1879 proceedings of the Institution of Mechanical Engineers, which are given in the following tables have been ever since con-

sidered as classic, the few later tests which have been made making little if any change therein.

TABLE XXI.

COEFFICIENT OF FRICTION AT VARIOUS SPEEDS WITH CAST IRON BRAKE SHOES ON STEEL TIRES.

No. of tests from which mean is taken	Velocity		Coefficient of friction		
	M. p. h.	Ft. p. sec.	Extreme Max.	Extreme Min.	Mean
12	60	88	.123	.058	.074
67	55	81	.136	.060	.111
55	50	73	.153	.050	.116
77	45	66	.179	.080	.127
70	40	59	.194	.088	.140
80	35	51	.197	.087	.142
94	30	44	.196	.098	.164
70	25	36.5	.205	.108	.166
69	20	29	.240	.133	.192
78	15	22	.280	.131	.223
54	10	14.5	.281	.161	.242
28	7.5	11	.325	.123	.244
20	Under 5........	Under 7........	.340	.156	.273
....	Just moving ...	Just moving....	....	....	.330

TABLE XXII.

EFFECT OF ELAPSED TIME ON COEFFICIENT OF FRICTION.

Speed M. p. h.	Coefficient of Friction				
	Start	After 5 sec.	After 10 sec.	After 15 sec.	After 20 sec.
20	.182	.152	.133	.116	.099
27	.171	.130	.119	.081	.072
37	.152	.096	.083	.069	....
47	.132	.080	.070	....	....
60	.072	.063	.058	....	....

From the above tables the maximum pressure to be applied to the brake shoes may be determined under the various service conditions in order to provide the required frictional tangential force. To determine what the limits of the latter are the coefficient of friction between wheels and rail must be known. This value varies widely with the condition of the rail, but may be safely assumed from 0.15 to 0.30 when the rail is wet and dry respectively. These latter values are coefficients of static friction which are greater than dynamic friction if other conditions are the same. For if the wheels are rolling, there is no relative sliding between wheels and rails and the frictional force to be considered is that necessary to start one body from rest upon the other and not that lesser force necessary to keep one body in motion upon the other. The maximum limit of brake shoe friction is now at once apparent, for it must not exceed the static friction between wheels and track. If it were to exceed that value the brake shoes would "lock the wheels" and the latter would "skid" on the rails with increased instead of lessened speed because of the lower value of dynamic friction thus suddenly brought into play between wheels and track.

Theoretically, cars should be equipped with braking apparatus which will be able to approximate as nearly as possible this maximum value for emergency stops, but since the braking force with hand brake equipment depends upon the strength of the motorman and with air brake equipment upon the variable air pressure, it is usually possible to "skid the wheels" on the average car if the brakes are applied too forcibly. Further, since Table XXI shows that the friction between brake shoe and wheel increases as the speed decreases during the braking period, a force applied to the brake shoes when braking is commenced which is slightly less than that necessary to lock the wheels may become sufficiently great to produce that result at lower speeds for the reason that the static friction between wheels and track remains constant. Every experienced motorman understands the results of such an application of brakes and releases and reapplies the braking pressure with less and less intensity as the car comes to a stop. Failure to do this results in too sudden a stop for comfort, a severe

chattering of the brake rigging and possible skidding, and incidentally marks an inexperienced or careless motorman.

Another factor which must be taken into consideration in stopping a car comfortably and safely is the condition of the track, the sudden and unexpected skidding of wheels and the consequent sudden increase in speed having been the cause of many an accident. It is a peculiar fact that with a very thin film of water on the rail due to a slight shower, the friction is greatly reduced over that of a dry rail or even a thoroughly wet rail. Again the crushing of leaves or weeds on the tread of the rail or too generous a supply of track grease often make it impossible to stop on a section of track thus affected without the use of sand. Cars

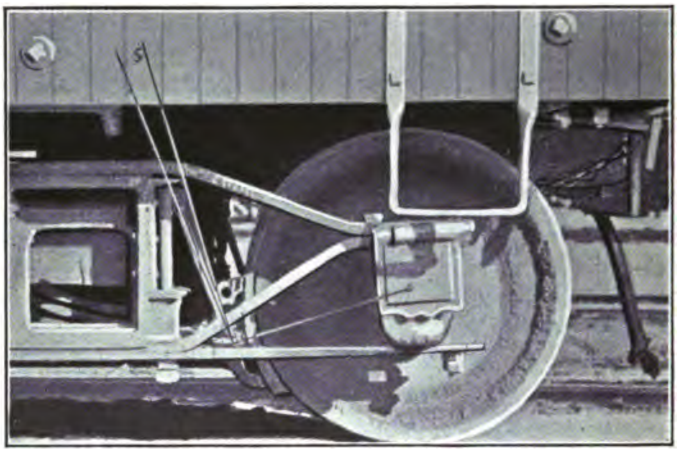


FIG. 111.

have been known to slide down long hills with tracks thus covered while the motorman was utterly powerless to reduce the speed, even with the reversal of the motors. Most roads, therefore, provide a generous supply of sand on each car not only, but require the track repair crew to keep the track free from leaves, grass and weeds.

Braking Forces.—If the car is to be stopped by the application of pressure to the brake shoes bearing upon the car wheels as is ordinarily the case, it will be noted at once that the forces tending to move the car forward and those applied as resistances

to stop the motion do not lie in the same horizontal plane, the former acting at the center of gravity of the combined loaded car body and trucks and the latter at the contact between wheels and rails. The result is easily seen to be a tendency to raise the rear of the car from the track, the forces acting at the center of gravity of the car having a moment about the front truck. In addition, there is a tendency for the rear wheels of each truck to lift from the track for the reason that the forces at the king pin and center of gravity of the truck have a moment about the front wheels. The resulting effect is that the pressure is lessened between car and rails at the rear and the static friction depended upon for braking thereby reduced. Either the braking pressure

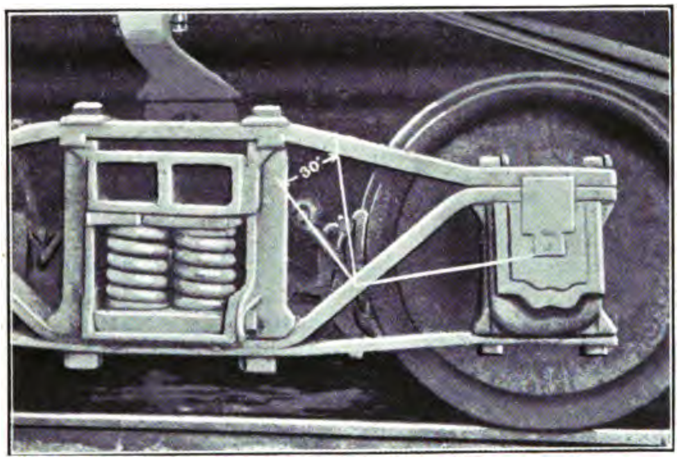


FIG. 112.

must be reduced upon the rear truck over that of the front truck and that of the rear wheels of each truck over that of its front wheels or else all braking pressures must be lowered considerably below that possible at the front end of the car. That the braking pressures on the rear truck cannot be made less than those of the front truck by any change in the leverages on the car in the case of double-end cars is obvious. With single-end interurban cars such provision is often made. There is, however, a method of hanging brake shoes with the supporting link of the brake shoe out of line with the tangent to the wheel at the center of the shoe

which will vary the pressure between shoe and wheel with the direction of operation of the car. This may be illustrated by referring to Fig. 111 where the brake shoe hanger is 5° out of line with the tangent. With the car moving toward the right the frictional force at the shoe is balanced by a force of compression in the hanger plus a force normal to the car wheel proportional to the sine of 5°. This is added directly to the brake shoe pressure. If the car be operating toward the left, thus making the wheel shown in the figure the rear wheel of the truck, the frictional force produces a tension in the brake shoe hanger and a force proportional to the sine of 5° tending to reduce the pressure exerted by the brake rigging. Whereas this effect may be increased by increasing the angle between brake shoe hanger and tangent, too great an increase of this angle tends to bind the shoes upon

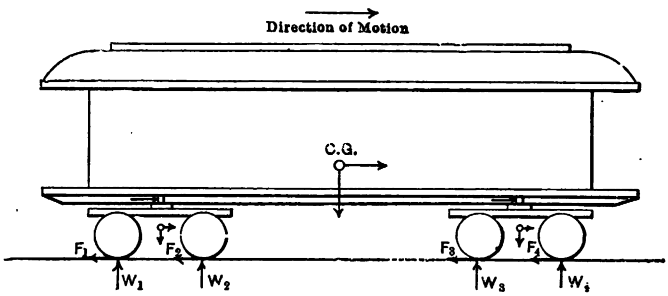


FIG. 113.

the wheel as in the case of a toggle joint causing chattering of the brake rigging and flat wheels. Such a condition often found on car trucks is Illustrated in Fig. 112, where the angle has been increased to 30°.

In order to determine the concrete value of the resultant weight upon each wheel of a car, it is necessary to analyse all the forces acting thereon as outlined in Fig. 113 and to balance the moments of the forces about any single point as in any problem in mechanics. A sufficient number of equations will result to permit the weights (W_1), (W_2), (W_3) and (W_4) to be calculated and the corresponding frictional forces (F_1), (F_2), (F_3), and (F_4) determined through the agency of the coefficient of friction. In determining the above equations, it must be remembered that

the rotative inertia of the car wheels, axles, and motor armatures must be overcome in stopping the car as well as the translational inertia of car and trucks.

Whereas, the method above outlined will result in a very accurate analysis of the various weights and forces involved, it would be seldom indeed, that the electrical engineer would make such a calculation before writing specifications for car equipment. The effect of reduction of pressure at the rear of the car may be taken roughly at 15 per cent. and the brake rigging designed for a resultant brake shoe pressure corresponding to 85 per cent. of the actual static weight on wheels.

Braking Equipment.—It has been previously stated that the

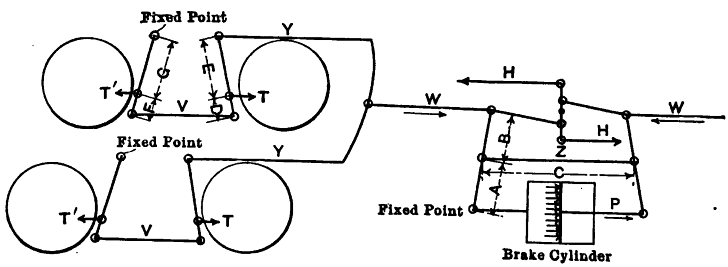


FIG. 114.

hand and air brake systems are now almost universally used in electric railway service. The former is used alone upon small city cars, while both systems are universally applied to the heavier suburban and interurban equipment. Where both are used the same brake rigging is installed for both, the leverages in the case of the hand brake being greater to make up for the relatively small pull the motorman can exert as compared with the air pressure of the brake cylinder. A typical brake rigging installation may be seen in Fig. 114, the operation of which will be self-explanatory if it be stated that the piston of the air brake cylinder is forced forward by air pressure, when the proper valve position is provided by the motorman, just as the piston of a steam engine is operated. The principal dimensions of the various parts of the equipment of several interurban cars of the Middle West are given in Table XXIII, all of which refer to Fig. 114. The ratio between brake shoe pressure and brake cylinder pressure may be

readily obtained from the following equations. With this ratio known the air brake pressure per square inch of piston area may be quickly determined for various desired brake shoe applications.

TABLE XXIII.

DIMENSIONS OF AIR BRAKE EQUIPMENT.

Interurban car	Dimensions of levers in inches						
	A	B	C	D	E	F	G
1	10.5	9.0	....	5.0	16.0	4.0	13.0
2	9.5	9.5	....	7.0	18.0	7.0	18.0
3	12.0	23.0	....	6.0	16.0	5.0	15.0
4	11.0	17.0	35	5.0	12.5	5.0	12.5

Let (P) represent the total force on the piston of the brake cylinder and designate the resultant forces in the various links by the letters appearing upon the links in Fig. 114.

$$P = \text{Air pressure} \times \text{area piston}. \qquad (103)$$

From the ratios of lever arms the following equations may be derived:

$$Y = \frac{W}{2} = \frac{PA}{2B} \qquad (104)$$

$$T = \frac{Y(D + E)}{D} \qquad (105)$$

$$V = \frac{YE}{D} \qquad (106)$$

$$T' = \frac{V(F + G)}{G} \qquad (107)$$

If the ratio between total pressure exerted by all brake shoes to brake cylinder pressure be signified by (R).

$$R \text{ (for a double-truck car)} = \frac{4(T + T')}{P} \qquad (108)$$

Substitution in the above equations of values for the four cars

in Table XXIII results in the forces listed in Table XXIV with a 10 in. cylinder and maximum air pressure of 70 lb. per sq. in.

TABLE XXIV.

FORCES ACTING IN AIR BRAKE EQUIPMENT.

Interurban car	Forms in pounds						
	P	W	Y	T	V	T′	R
1	5,497	6,400	3,200	13,450	10,250	13,400	19.6
2	5,497	5,497	2,748	9,830	7,080	9,830	14.4
3	5,497	2,860	1,430	5,250	3,820	5,100	7.54
4	5,497	3,550	1,775	6,210	4,430	6,210	9.06

From the above table it will be seen that the multiplying power of the brake levers on four interurban cars taken at random varies from 7.5 to 19.5.

It should not be forgotten that the above forces are based upon an emergency application of air of 70 lb. pressure which is seldom used. For an ordinary service application the forces would average less than one-half the above values.

A further calculation may be made from Table XXIII which is of value in determining the adequacy of the equipment for the service. Car No. 4 in this table weighs in the neighborhood of 25 tons. The total brake shoe pressure exerted on all wheels with a 70 lb. application of air is

$$8 \times 6{,}210 = 49{,}680 \text{ lb.}$$

Ratio of total brake shoe pressure to weight of car is 99.2 per cent. If the coefficient of friction were the same between shoe and wheels that it is between wheels and rails it would be possible to skid the wheels with an application of air slightly above 70 lb.

Brake Rigging.—The levers by means of which the braking force is transmitted from hand brake or brake cylinder to brake shoes are of heavy strap iron linked together with steel pins provided with cotter pins and supported from the under frame of the car by means of strap iron stirrups. Links in tension are

usually constructed of 1 in. round iron rod. The circle bar between links (Y) and (W) Fig. 114 is provided with the truck together with a clevis which may be welded to rod (W) and which is so designed as to slide on the circle bar as the trucks swing with respect to the car body when turning a curve.

The hand brake consists of the familiar vertical ratchet crank

FIG. 115.—Straight Air Brake Equipment.

or wheel in the motorman's cab which winds up a chain under the car vestibule, this chain exerting a tensile force at H, Fig. 114.

Straight Air Brake Equipment.—The air brake equipment in its simplest form consists of a motor driven air compressor, a storage reservoir, a brake cylinder, a governor, two engineer's valves with gauges for double end equipment, a system of levers,

complete piping equipment and usually one or more air whistles to act as signals. Fig. 115 represents the apparatus above outlined. The compressor, reservoir, brake cylinder and piping are supported from the under frame of the car. The governor is often placed on the car floor under one of the end seats, while the remainder of the equipment is in the motorman's cab.

The air compressor is a direct connected pump and direct current 550 volt series motor connected between trolley and ground with only a snap switch, the governor switch and a fuse in circuit. The trolley connection is made between circuit breaker and trolley so that the compressor will not stop when the circuit breaker opens.

The governor is a pneumatically operated switch which can be adjusted to close the compressor circuit and thereby start the compressor when the air pressure falls below a predetermined value and which will automatically stop the compressor when the pressure reaches the maximum value desired. While there is a considerable range for which the governor may be adjusted, it is generally set to operate at about 70 and 90 lb. per sq. in. respectively.

The motorman's valve is of the three position type. The operating handle, when moved to the "service" position opens the valve between reservoir and brake cylinder and applies the brakes. The extent to which the handle is moved in this direction and the time during which it is left there determine the pressure applied to the brake shoes. If it be desired to retain this pressure in the brake cylinder the handle may be moved to the "lap" position where all valves are closed. The handle may be removed only when in this position. By throwing the handle to the position opposite to that of "service" into the "exhaust" notch the air in the brake cylinder escapes to the atmosphere and the brakes are released. It is a rather unfortunate fact that two types of air brake valves apply the air with opposite movements of the valve handle. This is rather confusing to motormen accustomed to one method when changing to another road using the other system.

Automatic Air Brake Equipment.—Contrasted with the above "straight air brake equipment" which is applicable to single

cars only, the "automatic air brake equipment" similar to that found on steam trains is often found on electric lines, especially in elevated, subway, and heavy interurban service where two or more cars are coupled together. The principal difference between this system and the one previously described is the addition of a second or auxiliary storage reservoir and the use of a "triple valve." A "train line" or continuous pipe under air pressure is provided throughout the train, rubber hose couplings with patented air tight knuckle joints permitting the ready closing of the line when shifting cars. The "triple valve," which is the vital part of the entire system, consists of a piston valve ordinarily balanced in a mid position by the auxiliary reservoir pressure on one side and the "train line" pressure on the other. When the motorman's valve is in the "service" position the train line is momentarily opened to the atmosphere and its pressure reduced sufficiently to cause the auxiliary reservoir pressure to move the triple valve piston to such a position as to admit air from the auxiliary reservoir to the brake cylinder and apply the brakes. This occurs on every car of the train. To release the brakes the motorman's valve in the "exhaust" position allows air to flow from the main reservoir to the train line and raise its pressure so that the triple valve is again balanced and the brake cylinder opened to the atmosphere. One of the most valuable features about this equipment is the fact that any leakage or breaking apart of cars, etc., which will reduce the pressure in the train line will set the brakes upon all cars of the train.

Quick Action Automatic System.—The automatic air brake as above described is applicable to trains up to about five cars in length. For the longer trains, however, the reduction in train line pressure requires an appreciable time to be felt throughout the length of the train. The resulting effect of some cars of the train braked with others free causes severe strains on the draft rigging, not to mention inconvenience to passengers. The "quick action automatic air brake system" is therefore applied to the longer trains. This is similar to the other with the exception that the "triple valve" is so designed as to feed both auxiliary reservoir and train line pressure into the brake cylinder. This procedure not only causes each car to aid in quickly reducing

the train line pressure throughout the train, but it decreases the drop in train line pressure which must be produced at the head car. In other words the action is cumulative throughout the length of the train.

In both the automatic systems the motorman is provided with a duplex gauge indicating both train line and main reservoir pressure. In the straight air brake system either a single gauge hand is provided to denote the reservoir pressure or two indications are given, one above outlined and in addition a second hand to show the pressure applied to the brake cylinder.

Friction Disc, Electric and Track Brakes.—Many types of special braking devices have been invented and tried out, involving friction discs bearing upon the planed inside surfaces of car wheels, magnetic brakes supplied with energy either from the trolley or the car motors used as generators, and track brakes consisting of shoes bearing upon the rail instead of the car wheels and often designed to grip the head of the rail with a variable pressure. While some of these devices have served admirably in special instances, especially as an additional safety device upon severe grades, they are not in sufficiently general use to warrant detailed description.

Reversal of Motors.—A method of stopping cars in cases of emergency, known as "reversing" consists in throwing the reverse lever to the reverse position and applying power to the extent of one or possibly two series notches of the controller. This, of course, tends to operate the car in the reverse direction and not only stops the car with a sudden jolt but is likely to damage the car equipment. It is therefore seldom resorted to, but in case of failure of the brake rigging or to avoid a collision, it is sometimes a valuable protection.

Motors used as Generators.—As a last resort, with no power supplied to the car, and with brake rigging damaged, there is yet another method of stopping the car. The reverse lever may be thrown into the reverse position and the controller handle swung into one of the parallel notches. The resulting connection causes one motor to operate as a generator, driven by the inertia of the car, thus supplying the other motor with power tending to operate the car in the reverse direction. This method may,

of course, be used if the power supply be present by throwing the circuit breaker to the open position.

With either of the above methods involving the use of electric power in stopping the car, great care must be taken not to skid the wheels as this condition prevents a prompt stop not only, but is likely to flatten the wheels as well.

Brake Tests.—It is often of great value to know the time and

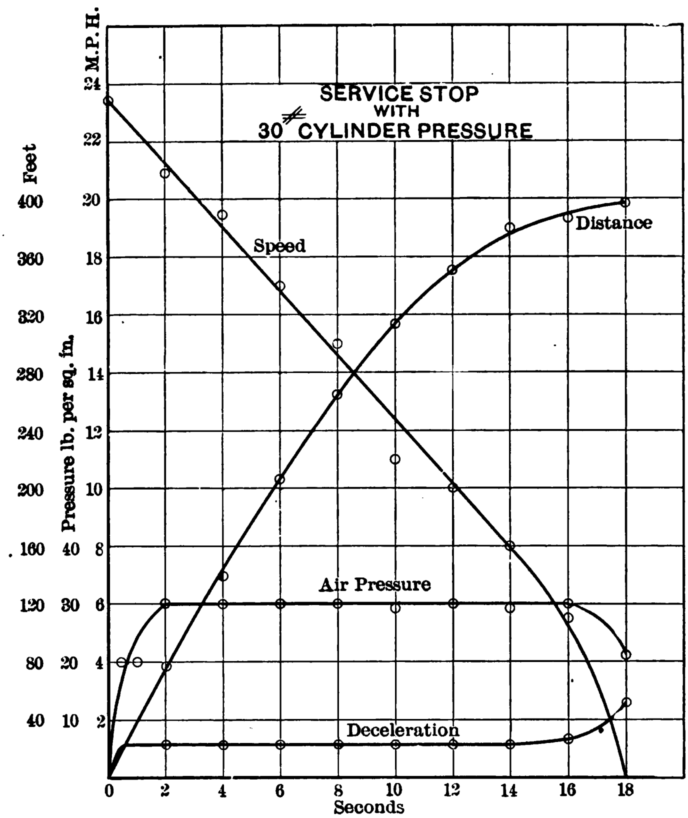


FIG. 116.

distance required in which to stop cars of various weights operating at different speeds. This is particularly true in case of accidents and court litigation. Whereas these facts may be predetermined mathematically as has been previously pointed out, the actual test of a car in service is often required as well.

In order to carry out such a test thoroughly, it is necessary to provide a method of determining speed of car, time between brake signal and stop and distance travelled during this period. It is also well in some cases to know the air brake pressure, the amount of wheel skidding and the motor current in case either of the reverse methods are used.

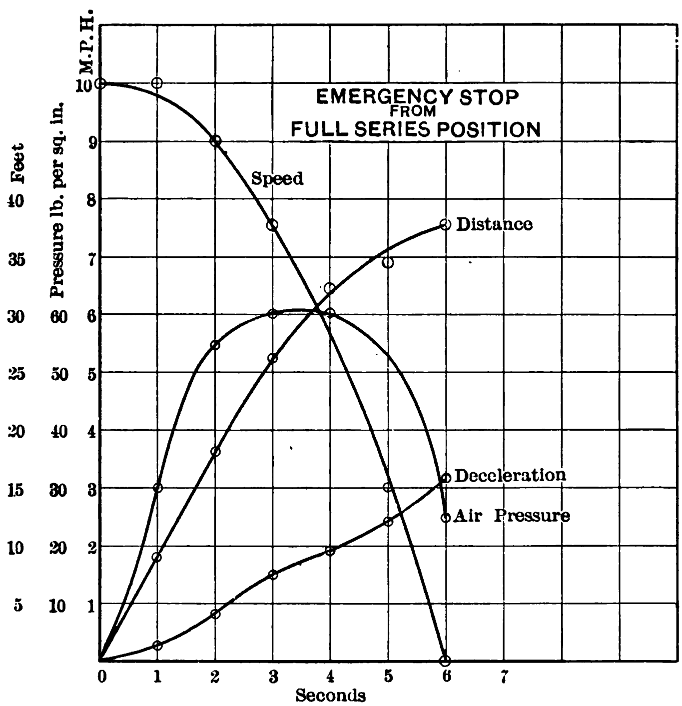


FIG. 117.

One of the most satisfactory methods of determining the speed at any instant is by means of a magneto generator, driven from the car axle, the voltage of the generator read from a voltmeter in circuit being directly proportional to speed.

The distance travelled during the braking period may be roughly determined from the revolutions of the car wheel or a similar wheel driven from the car axle, which may be caused to make electrical contacts every revolution. If any skidding occurs, this method becomes valueless. A method which has

worked admirably in recent tests at Purdue University is to give the braking signal by means of a revolver from which a ball is shot beside the track, thus marking the start of the braking test very accurately. The distance required to stop may then be measured along the track from this point with a steel tape.

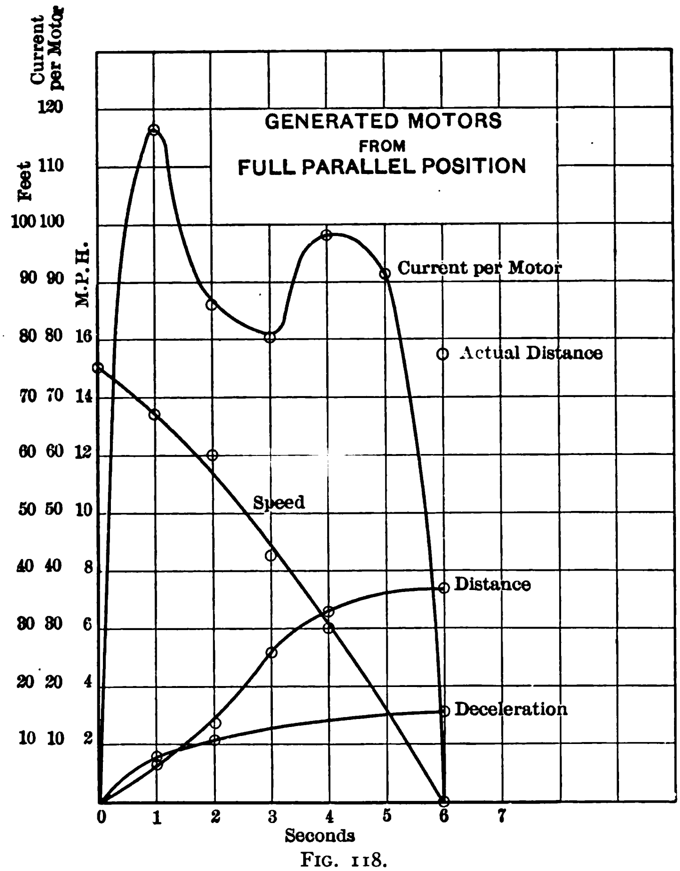


FIG. 118.

All of the data of the test may readily be arranged for an automatic graphical record upon a single paper chart, thus illustrating clearly the desired values at any given instant.

The results of such tests are best shown by curves similar to those of Figs. 116, 117, and 118 which represent braking tests made with the Purdue University Test Car[1] of approximately

[1] Thesis, Purdue University, 1911, by Luhrman, Blaschke and McLean.

25 tons weight equipped with brake rigging designated as car No. 4 in Table XXIII. While it is believed that these figures are in general self-explanatory, especial attention should be called to the amount of skidding which took place in the stop by means of generated motors, Fig. 118, and also to the fact that the speed-time curve is seldom a straight line as is assumed in theoretical calculations. The error in such an assumption, however, is obviously small.

The results of all the tests made upon the above car are given in some detail in Table XXV and may prove of some value in approximating possible stopping time and distance under other conditions.

TABLE XXV.

BRAKING TESTS.

Kind of stop	Air press. Lb. per sq. in.		Time to stop seconds	Distance to stop feet	Distance skidded feet	Deceleration m. p. h. p. s.		Speed m. p. h.		Current per motor max.
	Max.	Avg.				Max.	Avg.	Max.	Avg.	
Emergency	65.0	56.2	12.5	320.0	......	2.3	2.06	23.0	12.75	....
Gen. motors	....	....	6.0	70.7	33.2	3.1	2.14	15.0	8.3	116.5
Gen. motors and hand brakes	....	....	4.0	45.3	8.1	3.0	2.5	12.0	7.0	110.0
Reversing motors	....	....	5.0	100.0	100.0	3.6	3.6	18.0	....	165.0
Ordinary service	42.0	28.0	14.0	220.0	....	1.65	1.41	22.5	11.3	....
Service 30 lb. air	30.0	25.6	18.0	396.0	....	2.6	1.17	23.0	13.0	....
Service 40 lb. air	38.0	31.3	9.0	268.0	....	2.2	1.85	19.0	8.7	....
Service 60 lb. air	57.5	46.8	7.0	181.8	....	3.0	2.64	21.0	12.4	....
Service 70 lb. air	60.0	42.9	6.0	193.8	....	6.25	3.15	22.0	12.2	....

CHAPTER VI.

CAR HOUSE DESIGN.

As the modern car house not only provides storage for the rolling stock, but also furnishes room for inspection and repairs and often includes the shops and offices of the railway company, much thought must be given to its location and design.

Location.—Too often a lot for a car house is secured before the size or requirements of the latter are determined, thus requiring that the car house and track layout be fitted to the lot. This procedure results in a limited and unsatisfactory design. A site of sufficient size for all the above functions of the car house, with proper consideration for future growth, should be selected in the most convenient section of the city from an operating standpoint. Care must be taken to make sure that all necessary track privileges may be obtained from the city authorities before the site is finally purchased.

In the case of the interurban car house, a location for the latter, together with the shops, offices and often the power house or substation is selected at about the middle of the line, although where the interurban road is operated by the company controlling the traction systems of the terminal cities the cars may be handled by the city car houses. This plan often offers the advantages of lessened fire risk, smaller dead mileage of cars, improved freight and express accommodations and better or more congenial homes for employees. For the advantages to be gained by locating near the power house, as well as for an outline of many considerations to be taken into account in deciding upon the proper location, reference should be made to Chapter V of Part II.

The fire risk of a car house is great and abundant water supply and other fire protection should be available not only, but care should be taken to avoid all fire risk from adjoining buildings. The sub soil should be examined with a view toward determining the foundations and piling necessary, although with the lighter

and more equally distributed weight of the car house this is not such a vital factor as with the power station. Good drainage and suitable sewer connections should, however, be available or easily provided.

Layout of Tracks.—One of the first questions to be decided is the percentage of total cars owned for which cover shall be provided. This is a question upon which railway managers differ widely. At the 1907 Convention of the American Street and Interurban Railway Association a committee appointed to investigate this question assumed the case of a car house accommodating 84 cars under cover as compared with a similar design capable of housing but one-third this number. The estimated costs were $105,000 and $45,000 respectively. With fixed charges at 12 per cent., this represents an annual saving of $7,200 or $85 per car. A study of the requirements of this road showed that all cars not in service between 6 A.M. and midnight could be housed by the small structure and of course this would involve different cars on different days. The larger car house and the increased annual outlay includes simply the ability to house two-thirds more cars from midnight until 6 A.M. Since the $85 per car will nearly provide for repainting and varnishing a car each year and as the added deterioration of the car during this period of day when out of service is not great, this particular case seems to favor open storage. Opposed to this evidence probably the most important argument for complete car storage is the fact that the equipment will certainly receive better attention from inspectors and repair crew if all cars are stored within the car house, especially in bad weather.

The next question of importance is whether a single or double-end house is desired. The latter type provides more ready movement of cars through the house and aids greatly in clearing the house in case of fire. Where a whole block or two intersecting streets are available it is often customary to form an operating loop through the car house for the cars when in regular service with regular inspections as they stop over the inspection pits. A rather complicated example of this construction is shown in the plan view of Fig. 119, representing the new Park Terminal car house in Baltimore. The principal objections to

the double-end arrangement are the difficulty in keeping tracks clear for through operation, the large amount of special track work required and the added difficulty in heating.

Whichever of the above designs is decided upon, depending largely upon local conditions, the problem remains to so connect the various tracks of the car house with those of the main line that the greatest possible flexibility of car movements within the yard may be had without interference with main line traffic and without obstructing the main track with more special work than

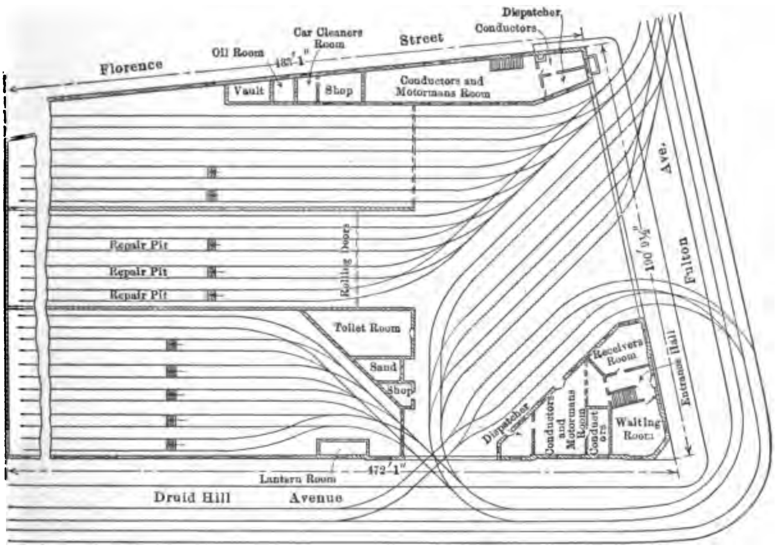


FIG. 119.

is absolutely necessary. Figs. 120 and 121 illustrate several typical methods of solution for this problem. Case (A) introduces several switches into one of the main tracks, but makes no connection with the second main track. A more flexible arrangement is shown in Case (B) where a cross-over is provided to the second main track in addition to one located in the car house. The latter is often found very useful, but its installation depends very much upon the availability of the special work in front of the car house for switching purposes. If the special work in the main line be objected to, Case (C) may offer a satisfactory solu-

tion, requiring necessarily more yard room. The design of Case (D) uses an extra or "gauntlet" track in the street for switching, while (E) is similar to (B) with the exception that the operating tracks are on the right of the storage house. If space will permit, (F) Fig. 122, offers an ideal arrangement, allowing the through cars to pass through the car house for inspection or minor repairs

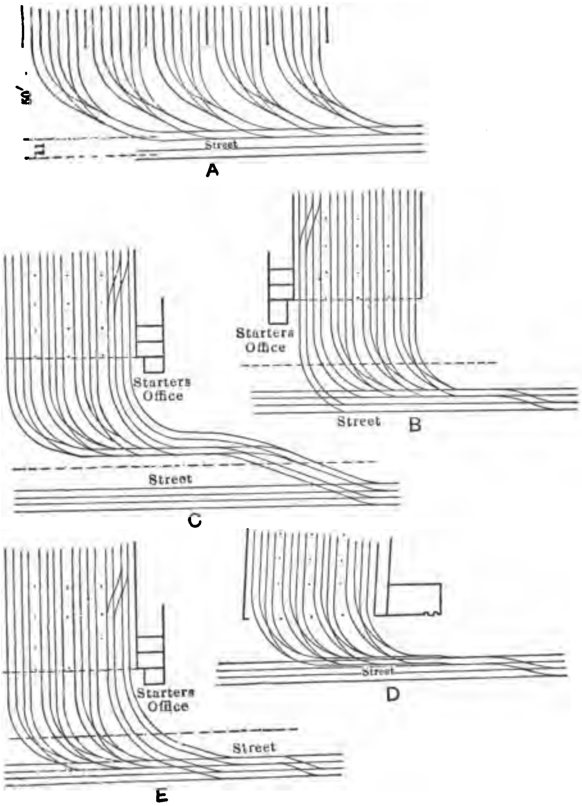


FIG. 120.

if desired and relieving the main line of all special work. It may also be used as a "Y" for turning cars which must operate single-ended. Designs (G) and (J) have been termed "bottle" entrances involving the special work within the car house because of building conditions. (H) may be used often in interurban service where land is cheap and the car house may be placed at

some distance from the main track. Case (I) involves the use of the third track in the street and therefore is limited to use with wide streets only.

The special work required for any of the above entrances should be of girder rail with manganese hardened centers regardless of the type of rail used in the street and car house.

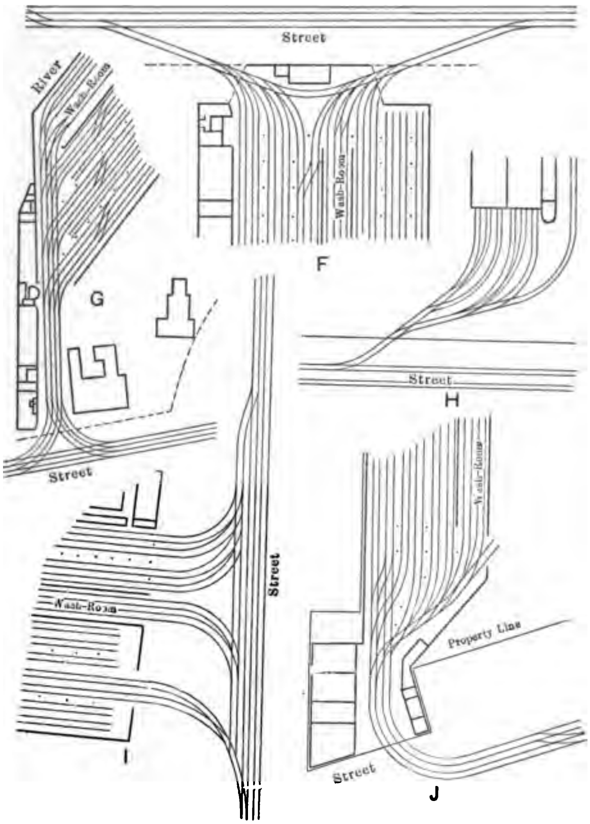


FIG. 121.

This is especially true in cases in which the regular street traffic must pass over the switches and frogs as well as the cars entering the car house.

Transfer Table.—The use of a transfer table in the car house often does away with much of the special work. This transfer table consists of a large truck operating upon a pair of depressed

rails laid across the car house with its upper surface flush with the floor and bearing sections of rail matching those of storage house and outgoing tracks. A car may be run on this table in either direction, be transported transversely of the car house and run off on another track. The table may be operated by hand in small installations, but is ordinarily driven by an electric motor. A typical installation may be seen in Fig. 122. Although the transfer table may be found in many city car houses, it is seriously objected to by many because of the time required to shift cars, especially in case of fire, and the space taken up thereby,

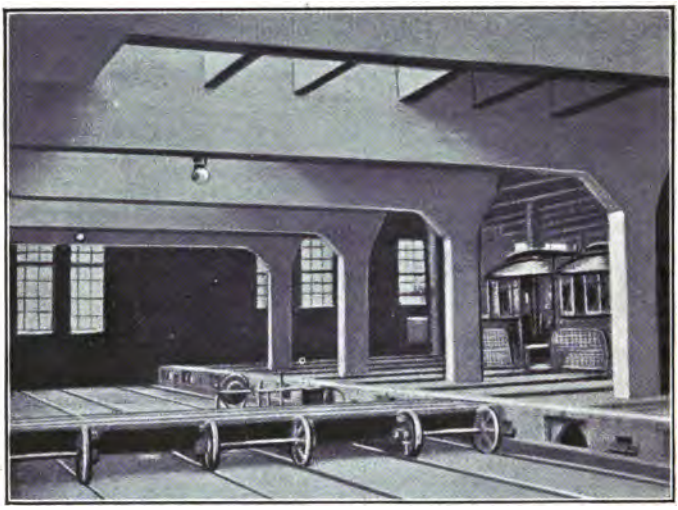


FIG. 122.

which might otherwise be available for storage. To obviate these objections the "flush" transfer table is used to some extent, the cars being run up to the table on a slight gradient, the table trucks operating on a transverse track flush with the floor.

Building Design.—With the above questions determined the design of a suitable building for a car house is a relatively simple matter. The two factors to be kept constantly in mind are ease of handling and repairing cars and fire protection.

Fire Protection.—Car houses are recognized to be considerable of a fire risk and many serious fires have consumed many

thousand dollars' worth of rolling stock in a surprisingly short time, the entire duration of several such fires being barely more than 30 minutes. In many instances where there is a spacious yard room outside, the house rails are stoped toward the entrance so that the cars will coast out of the barn if brakes are released. In other cases many cars have been saved in case of fire by throwing the controller handle to the first notch and allowing them to run out without attendance.

Not more than three tracks should be enclosed without a fire-proof partition and a single fire-proof section should not contain more than $200,000 worth of rolling stock as stipulated by the Fire Underwriters. The best design is either brick walls with heavy mill type roof construction of fire-proofed timber or rein forced concrete throughout. For the latter construction see Fig. 122. Steel truss roof construction has proven very dangerous in cases of fire as the roof falls in very quickly, thus cutting off all possibility of getting out the remaining cars. Curtain walls of cement plaster on wire lath are often installed in long houses, separating the storage space into several fire-proof compartments. The front of the house and these curtain walls are provided with steel rolling doors. Opinion is divided regarding the advantages of timber roof trusses over posts for roof supports. The latter of course obstruct the working area somewhat, but are often used to advantage for lighting outlets, sprinklers and the convenient support of fire fighting equipment. Automatic sprinkler systems are now being rapidly installed on ceilings and in aisles between cars for additional and prompt fire protection. These are supplied with sufficient head of water either from the city high pressure system or from a tank especially installed upon the premises. The appearance and relative dimensions of a typical car house elevation may be noted in Fig. 123.

Pit Construction.—For convenience in inspection and repair, from 30 to 50 per cent. of the tracks in the car house are pit tracks, *i.e.*, the floor between the rails is depressed several feet and cemented as shown in Fig. 123 in order that the under portion of the car may be accessible. It has also been found convenient to depress a portion of the floor between adjacent tracks by one or two feet for convenience in packing journal boxes, etc.

Heating.—Car houses are heated principally by either steam or hot water, coiled pipes being located in pits and upon the lower portion of all walls. The boiler room, if not in a separate building, must be carefully protected by fire-proof walls. The heating of car houses is at best, an unsatisfactory problem, especially in cases where the end doors must be continually open for the operation of cars.

Floors.—The floors in small storage car houses are sometimes of gravel fill. This is not to be approved, however, on account of the impossibility of keeping such a floor in a sanitary condition. Heavy timber flooring is probably most often found, but it should

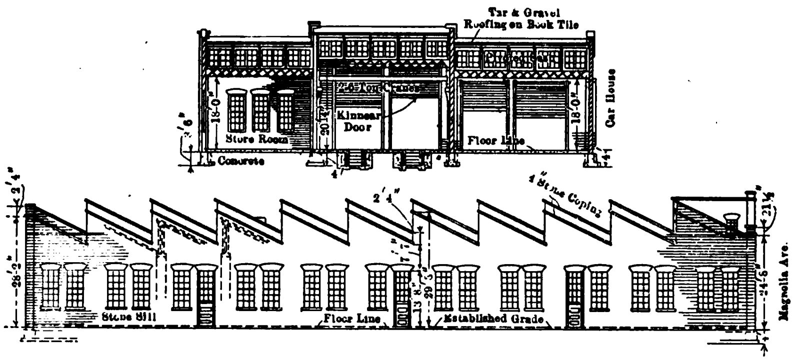


FIG. 123.

be avoided if the expense of concrete with cement finish can be seriously considered. Often the latter can be constructed with cinders from the power station without great expense and will prove the most satisfactory of all car house floors. Since substantial piers must be laid for the track foundations in whichever form it may take, the floor is generally supported therefrom.

Lighting.—Incandescent lighting by means of five light series groups of lamps connected between trolley and ground is often used in smaller installations, but a low voltage ungrounded supply is much preferable. Lights spaced every car length in aisles are usually sufficient for general illumination if generous provision be made for pit lighting and outlets for portable lamps. Pit lighting particularly should be in conduit as illustrated in Fig. 124. General illumination for very large areas and for storage

yards may be furnished by means of arc lamps, but these are not popular for car house installation.

Offices and Employee's Quarters.—The arrangement of offices, employee's quarters and storage for raw materials and tools are dependent upon local requirements and will not be discussed in detail. The portion of the building containing the offices and employee's quarters is often of two stories and, where within the city limits, is designed to present a good architectural appearance. Many companies fit up spacious apartments for

FIG. 124.

the use of employees rather elaborately with recreation and reading rooms, sleeping quarters, baths, etc. Provision should at least be made however for making out reports and for comfortably spending spare time between "reliefs." An average plan may be seen in Fig. 125.

Repair Shops.—It is necessary to decide at first what the policy of the company is to be with regard to car repair and reconstruction. If a large interurban company is to make all repairs, reconstruct damaged cars and possibly build new cars, a very elaborate series of forge, wood working, machine and paint shops will be necessary. The majority of the smaller companies,

however, make only minor repairs, often sending away wheels for replacement or returning rather than install the lathes and hydraulic presses necessary for this work. Whereas the discussion of the former type of shop is beyond the scope of this treatise, especially as comparatively few of the roads are thus equipped, the following average list may be of value in planning the equipment for a small shop. The machines are listed approximately in the order in which they would be added with increased demands upon the repair shops.

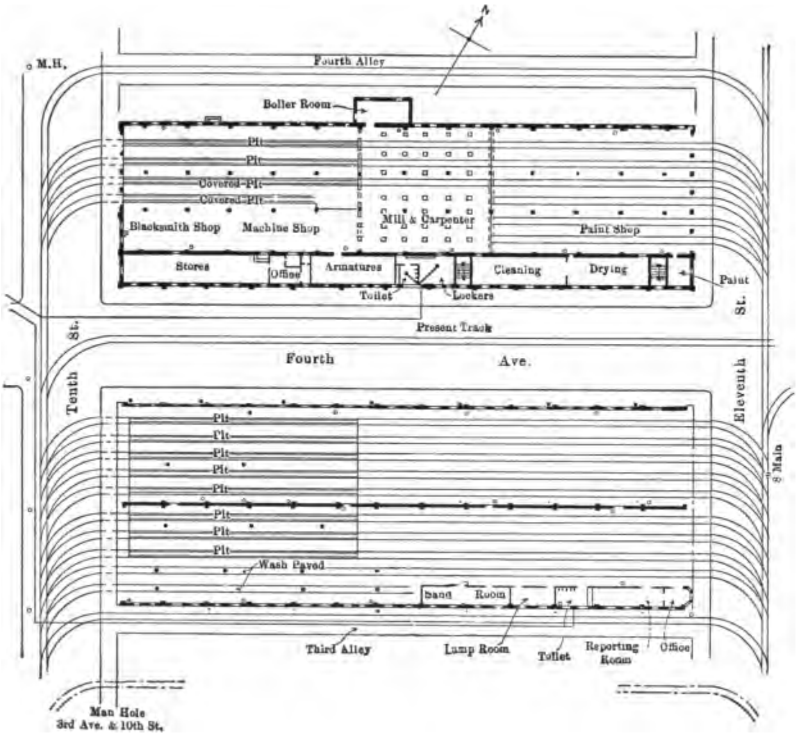


FIG. 125.

1 Screw-cutting lathe, 14 in. swing.
1 Vertical drill press, 24 in.
1 Tool grinding wheel.
4 Armature stands for rewinding armatures.
2 Forges.

1 Automatic power hack saw.
1 Oven for baking insulation.
1 Commutator slotting device.
1 Wheel turning lathe.
1 Hydraulic wheel press.

Whereas the small repair shop as well as the paint shop often occupy sections of the main car house, the large shops are housed in separate but adjacent buildings. Such an arrangement, showing typical floor plan details, will be found in Fig. 125.

CHAPTER VII.

Electric Locomotives.

With the recent rapid advance in electric traction there has come the successful design, construction, and operation of several types of electric locomotives. While the Baltimore and Ohio Railroad had previously operated electric locomotives in its tunnels for several years, the great impetus in electric locomotive development came in 1903 as a result of the requirement that the tunnels entering New York city be electrified. This was done largely as a safety precaution soon after a serious wreck in one of these tunnels due to the inability to read signals on account of the smoke inclosed in the tunnel. Likewise with the Cascade Tunnel of the Great Northern Railroad in Washington, experience with a train which parted in attempting to mount the severe grade of the tunnel with two steam locomotives, resulting in a delay of the train in the tunnel and the consequent overcoming, by poisonous gases and smoke, of the train crew and many passengers, led to the recent equipment of this section of the road with electric locomotives.

With the multiple unit control of motor cars, which has been previously described, developed to such an extent that long heavy trains of both motor cars and trailers are being operated successfully in elevated, subway and interurban service, offering a very flexible distribution of motive power and weight on driving wheels throughout the train, it might be expected that this method of propulsion would be applied to the heavier electrification of steam roads. As the traffic demands and the number of cars increased, motor and trail cars could then be added in the proper proportion so as to leave little excess capacity to operate at low efficiency as must often be the case with but one or two capacities of locomotives used for trains of widely varying weights and requirements.

In spite of these advantages of the motor car, the locomotive

is still found to be necessary in heavy trunk line service. Its advantages listed below can be made to overcome those of the motor car by dividing the service into three or four classes such as switching, suburban, express, passenger and heavy freight and designing different locomotives if necessary for two or more of these types of service, thus keeping the locomotive loaded approximately to its rated capacity. The advantages of the locomotive in heavy service may be listed as follows:

1. It eliminates necessity of re-equipping present cars as motor cars.

2. It eliminates necessity of wiring some of the present cars with train cables for use as electric trailers.

3. Ease in making up trains regardless of whether they have been electrically equipped or not—*i.e.*, the electric locomotive makes use of present cars without change therein.

4. Not necessary to make up trains in certain order with proper number and location of motor cars therein.

5. Ease in reaching parts in locomotive for repair.

6. Make up of train not affected by failure of electrical equipment. Locomotive only and not several cars of train must be switched in case of electrical breakdown.

Granted that an electric locomotive is needed if trunk line service is to be electrified, a study of the various types of electric locomotives which are in use at the present time is of interest. With the many years of experimenting and practical experience with steam locomotives which have led to a most satisfactory design for the various types of service, advantage was taken of present steam locomotive design, and the electrical equipment added with as little change as possible. To this end the manufacturers of steam locomotives and electrical machinery have coöperated to a marked degree in developing the new product.

In the early locomotives it was believed to be necessary, however, to mount the motors on the driving axles between drivers as in the case of motor cars with consequent limitation in capacity of motors if the present gauge of track and short wheel base are to be retained. The change of track gauge was of course practically impossible with the present installation of standard gauge roads in the country and an increase in the length of wheel base in-

troduced difficulties in rounding curves. In fact, any limitation upon the flexibility of the truck and the free and independent vertical and transverse movement of individual axles with irregularities in the track tends to move the entire mass of the locomotive, thus introducing bad riding qualities and vibrations which

FIG. 126.

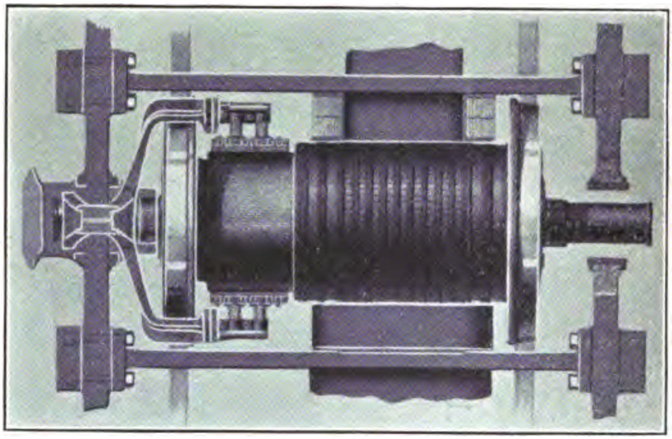


FIG. 127.

become dangerous at high speeds. An attempt was first made, therefore, to vary the design of the large interurban motors to gain greater capacity upon the limited size of trucks and later to remove the motor from the truck axles, as will be shown below.

The New York Central locomotive, Fig. 126, of the direct cur-

rent type, a plan view of whose motor is shown in Fig. 127, marked a radical departure in railway motor design. As will be noted from the figure, the motor is bipolar, the magnetic circuit involving a portion of the truck frame with internally projecting laminated iron poles with vertical faces, between which the armature, mounted directly on the truck axle, might vibrate in a vertical direction with the irregularities in the track. This

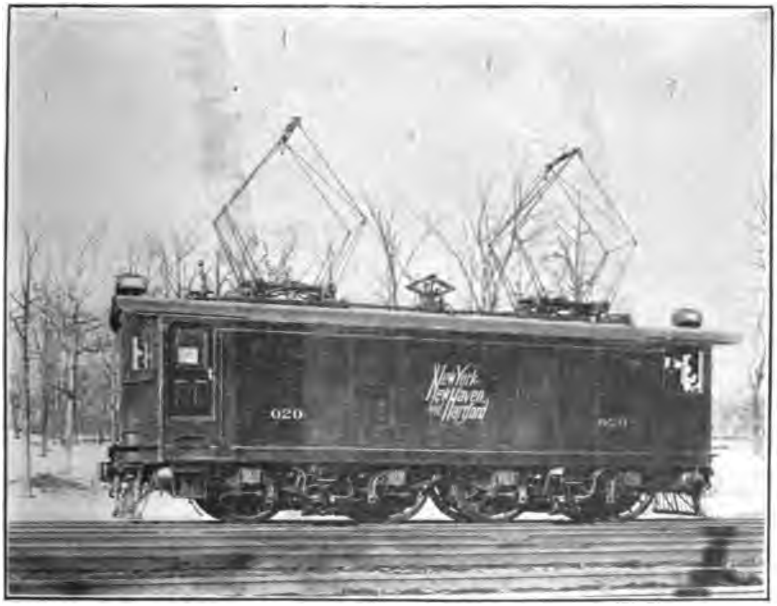


FIG. 128.

design, of course, considerably increased the capacity possible in the limited space on the truck, eliminated many of the disadvantages of the small air gap and gave considerable flexibility to the relative movement of armature and field. It also lowered the center of gravity of the locomotive below that of its steam railroad competitor and increased the dead load per axle, both of which changes have been considered as disadvantages by some engineers.

The locomotives of the New York, New Haven and Hartford Railroad, Fig. 128, which were developed soon after the above for operation upon the 11,000 volt single-phase system of the

above company not only, but also upon the 600 volt direct-current system of the New York Central Railroad entering New York City still retained the motors concentric with the truck axles and between the driving wheels as will be seen from Fig. 129, but reduced the dead weight upon the axles by supporting the armature upon a quill, concentric with, but surrounding the driving axle with a space of 5/8 in. between axle and inner circumference of quill. The torque was transmitted from armature

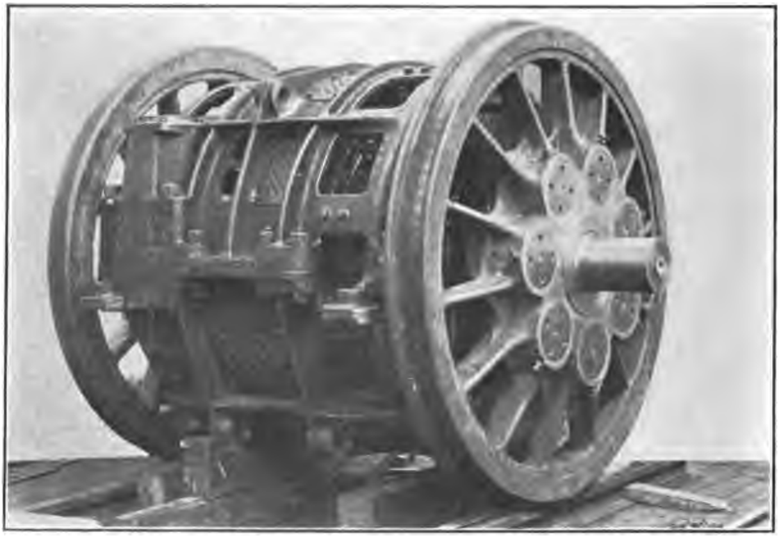


FIG. 129.

to drivers by means of seven driving pins, spring borne in recesses in the driving wheels as shown in Fig. 130. This allowed the axle considerable motion independent of the armature not only, but permitted the motor field and frame to be rigidly supported upon the truck.

After some few years of experience with the operation of the above locomotives and a careful study of their characteristics as compared with steam locomotives, the principle problem in design seemed to be resolved to that of the transmission between motor axle and driving wheels. Messrs. Storer and Eaton in a recent paper before the American Institute of Electrical Engi-

neers[1] have presented this problem in a very concise form and because of its importance in electric locomotive design and as designing engineers in both this country and abroad are at variance regarding the best method of transmission to adopt, a statement of the various types in use, together with illustrations of each have been taken from the above paper and are herein included.

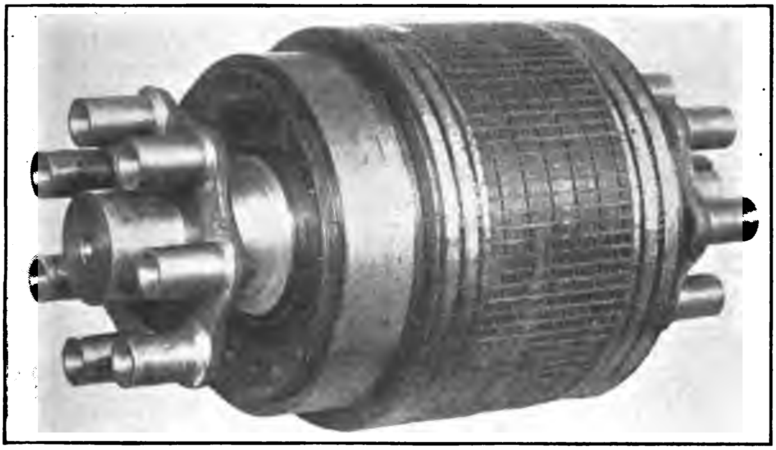


FIG. 130.

a. "Gearless motor with armature pressed onto driving axle, 'New York Central,' Fig. 131 a.

b. "Gearless motor with armature carried on a quill surrounding axle, and driving the wheels through flexible connections, 'New Haven Passenger,' Fig. 131 b.

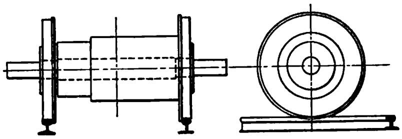
c. "Geared motor with bearings directly on axle and with nose supported on spring-borne parts of locomotive, 'St. Claire Tunnel,' Fig. 132 c.

d. "Geared motor with bearings on a quill surrounding axle, and (1) nose supported on spring-borne parts of machine (New Haven Car, Fig. 132 d) and (2) motor rigidly bolted to spring-borne parts of machines,

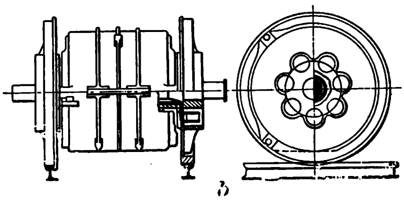
[1] The Design of the Electric Locomotive, by N. W. Storer and G. M. Eaton, A. I. E. E., Vol. XXIX.

the quill having sufficient clearance for axle movements, 'Four motor New Haven Freight,' Fig. 132 d′.

e. "Motor mounted rigidly on spring-borne parts, arma-

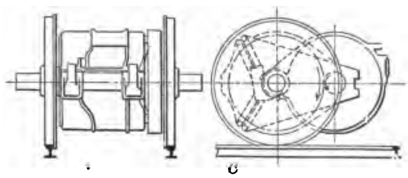


a

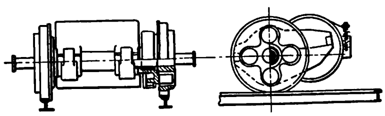


b

FIG. 131.



c



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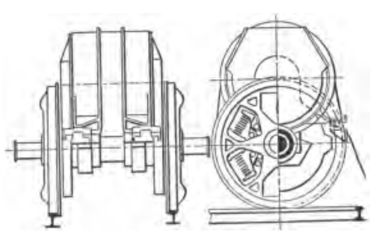
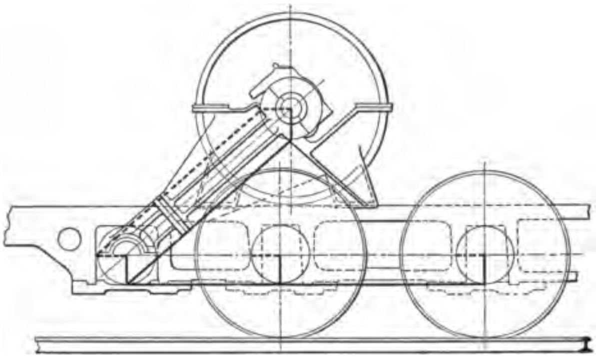


d′

FIG. 132.

ture rotating at same rate as drivers, power transmitted to drivers through cranks, connecting rods and counter shaft on level with driver axles. 'Pennsylvania,' Fig. 133.

f. "Motor mounting and transmission as in (e) but motor fitted with double bearings one part for centering motor crank axle and the other for centering the armature quill which surrounds and is flexibly con-

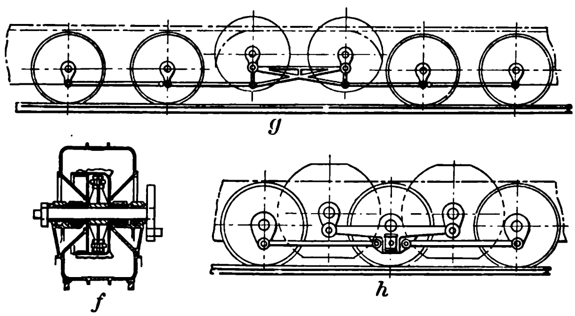


e

FIG. 133.

nected to the motor crank axle. 'Two motor New Haven Freight,' Fig. 134 f.

g. "Motors mounted on spring-borne parts, armature rotating at same rate as drivers, power transmitted to drivers through off-set connecting rods and side rods. 'Latest Simplon Locomotives,' Fig. 134 g.



g

f *h*

FIG. 134.

h. "Motors mounted on spring-borne parts, armature rotating at same rate as drivers, power transmitted to drivers through Scotch yokes and side rods. 'Valtellina Locomotives,' Fig. 134 h.

i. "Motors mounted rigidly on spring-borne parts, power transmitted through gears to counter-shaft, thence to drivers through Scotch yokes and side rods. Fig. 135."

It will be seen from the above that the locomotives of the Pennsylvania Railroad mark a rather radical departure from the designs previously described, having their motors above the trucks in the cab and returning to the connecting rods of the steam locomotives for transmission to the drivers. This design raises the center of gravity and permits practically unlimited

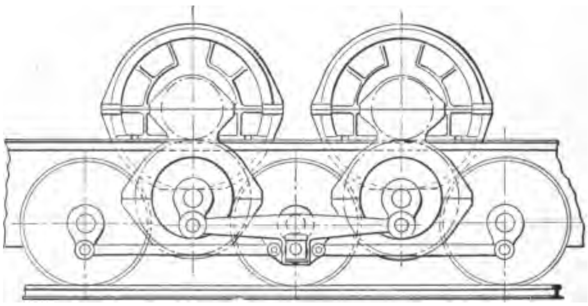


FIG. 135.

motor capacity in a single unit as its dimensions may be increased longitudinally at will and transversely by overhanging the driving wheels. This locomotive, which is designed in two sections which may operate separately, but which are intended for operation in pairs, is illustrated in Fig. 136, the slanting driving rod seen in the figure connecting with a single motor in each cab and being properly balanced by means of a counter-weighted crank disc.

Control Systems.—While the details of the specifications for the various types of electric locomotives built thus far in this country are concisely set forth in Tables XXVI and XXVII below, an additional word regarding the systems of control used may be of interest.

The New York Central locomotives having four 550 H. P., 600 volt direct current motors each operating upon a third rail distribution system have three running steps on their

controllers, the first with all motors in series, the second consisting of two groups in parallel series and finally all motors in series. The control is of the multiple unit type similar to that previously described for motor cars with a master controller and train cable with coupling plugs so that two or more locomotives may be operated together from a single engineer's cab.

FIG. 136.

The New York, New Haven and Hartford control equipment is the A. C. D. C. unit switch control operating two motors permanently in series. Upon the direct current system of the New York Central terminal system the series-parallel control is used and upon the high voltage alternating current section the auto-transformer steps the voltage down to six different values each of which is a permanent running voltage. About double this number of steps are required for smooth acceleration upon direct current, but because of the motor design used these extra steps may be secured in the series position by shunting the fields. This may be done in steps until the fields are at about one-half

their nominal flux rating without interfering with their successful operation. Each locomotive is equipped with four 250 H. P. motors nominal capacity, which are capable of exerting 200 H. P. each continuously. A pair of motors require 450 volts alternating current and 600 volts direct current for full rated speed.

Each section of the Pennsylvania locomotives contains a single motor rated at 2000 H. P. It is of the interpole (10 pole) type designed for use upon 600 volts direct current. The motors are controlled by the unit switch electro-pneumatic master control system previously described, having four running notches as follows:

1. Series connection with full field,
2. Series connection with normal field,
3. Parallel connection with full field,
4. Parallel connection with normal field.

These locomotives are provided with both third rail shoes and trolleys for either type of current collection.

As has been previously stated the locomotives of the Cascade Tunnel Division of the Great Northern Railroad are the only examples of polyphase traction in this country. In this particular case the installation of a motor with inherent constant speed characteristics seemed advisable where long runs over practically constant high grades at relatively low speeds were demanded. The control of the three-phase motors of these locomotives is similar to that for the variable speed slip-ring type, phase wound rotor induction motors used in stationary service. It consists in inserting resistances in series with the three phases of the rotor winding and gradually cutting out these resistances in one phase after another by means of a controller. By thus varying the resistance of but one phase at a time more accelerating points are obtained with less complicated wiring than when all three phases are changed simultaneously. This is done, however, at the expense of unbalanced currents in the motor and would not therefore be advisable under frequent starting conditions. The motors are of eight poles each, designed for a frequency of 25 cycles and employ forced ventilation for cooling. The voltage is reduced by transformers on the car from 6600 to

500 volts. A speed of approximately 15 m. p. h. is maintained in both directions upon an average and fairly constant grade of 1.7 per cent.

Data on Electric Locomotives.—The following tables taken from a paper by Westinghouse on "The Electrification of Railways" presented before the joint meeting of the American Society of Mechanical Engineers and the Institution of Mechanical Engineers in London in 1910 represent very concisely the details of design of American electric locomotives.

TABLE XXVI.

DATA ON WESTINGHOUSE ELECTRIC LOCOMOTIVES.

Built for	New Haven	Grand Trunk St. Clair Tunnel	Pennsylvania	New Haven	New Haven
Electric system	A. C.D.C.	A. C.	D. C.	A. C. D. C.	A. C. D. C.
Service	Passenger	Frt. & Pass.	Passenger.	Frt. & Pass.	Frt. & Pass
First placed in service	July 1907	Feb. 1908	17,000-mile test.	3,000-mile test.	Building.
No. in service or on order, May, 1910.	41	6	24	1	1
No. motors per locomotive.	4	3	2	4	2
Armature diameter, inches.	39½	30	56	39½	76
Core length, including vent. opening, inches.	18	14¾	23	13	13
Weight 1 motor, pounds	16,420	15,660	45,000	19,770	41,600
Wt. all motors on locomotive	65,680	46,980	90,000	79,080	83,200
Wt. all electrical parts	110,400	58,400	127,200	130,000	135,000
Wt. all mechanical parts	94,100	73,600	204,800	130,000	125,000
Wt. complete locomotive	204,500	132,000	332,000	260,000	260,000
Wt. on driving wheels	162,000	132,000	207,800	180,000	180,000
Wt. complete locomotive for A. C. operation.	196,000	132,000	D. C.	241,000	240,000
Max. guar't'd speed m.p.h.	About 86	30	About 80	45	45
Feature limiting speed	Track	Armature	Connecting rod.	Armature	Armature.
Max. tractive effort	19,200	43,800	69,300	40,000	40,000
Loco. wt. in excess of 18% adhesion Max. T. E., A. C. operation.	88,700	None	None	18,500	17,500
Designed for trailing load, tons.	250	500	550	1500 frt. 800 pass.	1500 frt. 800 pass.
Balance speed on level with above load.	About 75	About 25	60	35 frt. 45 pass.	35 frt. 45 pass.

TABLE XXVII.

DATA ON GENERAL ELECTRIC LOCOMOTIVES.

Built for	N. Y. C. & H. R. R.	Detroit River Tunnel	B. & O. R.R.	Great Northern	Paris-Orleans
Electric system	D. C.	D. C.	D. C.	3-phase	D. C.
Service	Passenger	Frt. & Pass.	Frt. & Pass.	Frt. & Pass.	Passenger.
First placed in service	July 1906	Tests completed.	March 1910	July 1909	1899
No. in service or on order May, 1910.	47	6	2	4	11
No. motors per locomotive	4	4	4	4	4
Armature diameter, inches	29	25	25	35¾	23½
Core length, including vent. opening, inches.	19	11½	11½	16¼	12
Wt. one motor, pounds	18,150	10,560	10,560	15,000	8,855
Wt. all motors on locomotive	72,600	42,240	42,240	60,000	35,420
Wt. all electrical parts	91,200	54,000	54,000	109,000	42,500
Wt. all mechanical parts	138,800	146,000	130,000	121,000	67,500
Wt. complete locomotive	230,000	200,000	184,000	230,000	110,000
Wt. on driving wheels	141,000	200,000	184,000	230,000	110,000
Wt. complete locomotive for A. C. operation.	D.C.	D. C.	D. C.	230,000	D. C.
Max. guar't'd speed, m.p.h.	75	30	55	30	45
Feature limiting speed	Track	Armature	Armature	Armature	Armature.
Max. tractive effort	47,000	67,000	61,000	77,000	37,000
Loco. wt. in excess of 18% adhesion Max. T. E., A. C. operation.	None	None	None	None	None.
Designed for trailing load, tons, Freight		900 on 2%	850 on 1½%	500 on	
Passenger		600 grade.	500 grade.	2.2% grade	
Balance speed on level with above load.	45 63	Frt. 20.5 Pass. 22	Frt. 26 Pass. 30	15	300 32

Although some arguments in favor of the electric locomotive as compared with its steam rival will be considered in a later chapter, it may be said in the conclusion of this discussion that the electric locomotive has accomplished thus far all that has been required of it, *i.e.*, to operate as satisfactorily as the steam locomotive under all conditions of service and eliminate the disadvantages coincident with smoke and dirt of the latter. It has also shown itself capable of accelerating more rapidly than its competitor, which particularly commends it where headway is short and stops are frequent. It can readily be designed for a draw bar pull considerably in excess of that of the largest steam locomotives. It has therefore found a permanent place in the

electrification of terminals and its future now seems to be one of further adaptation and adoption, although its depreciation and maintenance in comparison with the steam locomotive can hardly be intelligently compared at present.

Gasolene Electric Car.—Although not strictly confined to the function of a locomotive, the gasolene electric car should be given

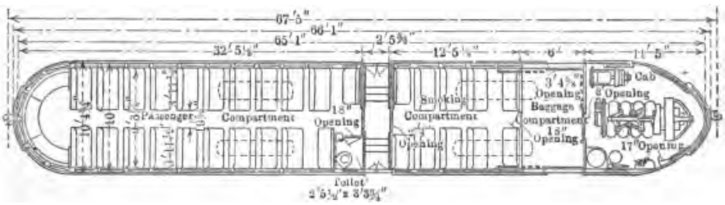


FIG. 137.

a place in the discussion of electric traction. In several instances, particularly upon small branch roads acting as feeders to trunk lines, where traffic is light and the installation of an electrical distribution system therefore unwarranted, and yet where the advantages of electric traction are worthy of serious consideration, the gasolene electric car has found a place. This car not only provides for from 40 to 50 passengers, together with a

FIG. 138.

baggage compartment, but also is a complete power plant, a flexible distribution system and a motor car combined. In the front end, above the floor, is located an eight cylinder, 100/125 H. P. four-cycle-gasolene engine, direct connected to an 80 K. W., 600 volt commutating pole direct current generator with exciter. A series parallel controller regulates the supply of current from

this generator to two 100 H. P. motors mounted on the front trucks. Additional flexibility of control is provided by the regulation of the voltage supplied to the motors by the variation of the generator field strength. The controller is also provided with means for regulating the engine ignition and the throttle. The car may be started, stopped, and reversed with the engine running continuously in one direction. A trolley is often provided by means of which the car may be operated on standard direct current trolley systems without change in the control equipment.

Reports from roads where these cars have been installed show a marked reduction in operating expenses and maintenance charges over those of steam operated trains, although their comparatively recent introduction has not permitted an accurate comparison over an extended period. A plan and elevation of one of these cars may be found in Figs. 137 and 138 respectively.

PART IV.

TYPES OF SYSTEMS.

CHAPTER I.

ALTERNATING CURRENT VS. DIRECT CURRENT TRACTION.

The problem to be discussed under the above caption is one that has received much attention during the past few years by steam and electric railroad officials, consulting engineers and electrical manufacturing companies. It has been the target of much discussion before technical societies and in the technical press, at times involving rather heated criticisms based upon both accurate engineering data and the enthusiastic prophecies of more or less prejudiced engineers. To sift out the salient factors in the case and outline the present status of the problem in a few words becomes, therefore, a difficult task.

Whereas the greater part of the discussion of this subject has been in connection with the electrification of steam roads, because of the prominence of the latter problem at the present time, before which the selection of a motive power for an interurban system immediately becomes dwarfed in magnitude, yet the consideration of this latter subject has purposely been made to precede that of "Electric Traction on Trunk Lines" because of its broader applicability to interurban systems, steam railroad electrification and possibly to city traction systems under some peculiar local conditions.

The systems which have sufficient advantages and for which complete power station, distribution and rolling stock equipment have been sufficiently developed to warrant consideration in this problem are the following.

1. Polyphase system,
2. Direct current 600 volt system,
3. Direct current 1200 volt system,
4. Single phase high voltage system.

The polyphase system, although least important, has been considered first for the reason that it may be readily classed separately and therefore omitted from the more detailed com-

parison which follows. The following characteristics of the polyphase system prevent its selection except for very special cases in which speeds may be low and constant, stops infrequent, service and grades heavy and fairly constant and operation with relatively low efficiency and complicated control not objectionable.

a. Constant speed characteristics,

b. Only the one-half and full speed operation efficient,

c. Control equipment complicated,

d. Unbalanced motor currents during acceleration,

e. Complicated distribution system involving either three trolley wires and three trolleys per car or two of each of the above with a track return for the third phase,

f. Cannot be operated upon direct current.

With the above explanation of the peculiar conditions under which the polyphase system must operate, which has thus far limited its installation to a single road in this country which has been previously described herein, the remaining three systems will be compared upon as nearly the same basis as possible. The peculiarities of each system, which may result in advantages or disadvantages depending upon local conditions in each installation, will be discussed in connection with the several determining and distinctive functions of the complete railway system.

Power Station.—The power station is not materially different for the three systems for a long road, involving as it does three-phase generating equipment and step-up transformers, together with the control of three-phase high tension transmission lines. If the single phase system be operated with a single-phase generating station, which is the exception rather than the rule, the first cost and size of generating equipment are increased for a given output, but the switchboard and control are slightly simplified.

Transmission Lines.—No material difference exists between the systems in regard to transmission, so long as three-phase transmission is adopted. The costs of these lines for all three systems are therefore practically identical. In the comparatively few installations where single-phase transmission might be adopted, the design and construction of the line is simplified

by the use of two wires in place of three, but for a given power transmitted and a fixed efficiency of transmission the cost of copper in the three-phase system is 25 per cent. less. This will usually more than balance the added installation and maintenance cost of the third wire.

Substation.—In the design of the substation is found one of the most marked variations in the three systems. As explained in a previous chapter the two direct current systems require the installation of transformers, synchronous converters or motor generators and switchboards in the substation, whereas the alternating current system calls for the transformers and automatic control switches only. This not only greatly reduces the first cost and maintenance in the latter system, but eliminates the services of an attendant. The elimination of this converting equipment will be found from the tables listed below to lower the first cost of substation to 27 per cent. and 37.5 per cent. of the 600 volt and 1200 volt substations respectively, while the operating costs are reduced respectively to 26.2 per cent. and 58.2 per cent. of the direct current substations. This is not clear gain on the part of the single-phase system, however, as it is partially balanced by the increased cost of rolling stock in the latter system.

In the relatively few instances in which the increase in distribution voltage in the single-phase system is sufficient to permit the economical transmission for the entire length of the line at trolley potential, the substation cost and maintenance is not only entirely eliminated, but the step-up transformers at the power station may usually be eliminated as well and the switchboard considerably simplified in consequence.

If the single-phase equipment were as well developed and standardized as the 600 volt direct current apparatus a lower depreciation factor might be applied to the former substation because of the relatively shorter life of the commutating machinery of the latter station, but it is probable that the allowance for obsolescence which must be made in the depreciation charges on recently developed equipment will compensate for any such reduction.

The first cost of the 1200 volt direct current substation is but 73 per cent. of the 600 volt station because of the lower current

value necessary for the same output, thereby reducing the size and cost of converters, cables and switchboard.

Distribution System.—As would naturally be expected the first cost of the distribution system decreases with increase of voltage, thereby favoring the 1200 volt direct current and 3300 to 11,000 volt single phase systems, especially in cases where traffic is sufficiently heavy to require the installation of the third rail in case of the 600 volt system. While this gain in first cost is admitted by the advocates of the direct current system in case of wooden pole line construction attention is called to the fact that with so-called "permanent" overhead construction, referring to the double catenary supported on steel bridges with long spans, the cost of the overhead is quite equal to that of the third rail construction.

Rolling Stock.—With the equipment of rolling stock the pendulum of efficiency, first cost and possibly of maintenance swings in the other direction favoring the direct current system.

Single-phase motors in their present stage of development are generally believed to be slightly inferior to the direct current motor in efficiency and quick accelerating qualities for a given rating. They are also considerably heavier for a given output, thus increasing the weight of car to be accelerated for a given traffic return. The above are general conclusions which will probably be conceded by both factions that have entered the rather extended controversy regarding the relative advantages and disadvantages of the single-phase motor for traction purposes. That this question is far from being decided is illustrated, however, in the following discussions of the subject before the American Institute of Electrical Engineers, which have been quoted herein for the double purpose of pointing out the unsettled condition of single-phase motor development at the present time as well as illustrating the various details of design under question.

Sprague points out the following differences between the single-phase and direct current motors.[1]

[1] "Some Facts and Problems Bearing on Trunk Line Operation," by Frank J. Sprague, A. I. E. E., Vol. XXVI.

"1. The input of current in one is continuous; in the other intermittent.

"2. One has a single frame, the electrical and mechanical parts being integral; the other has a laminated frame contained within an independent casing. Hence there is not equal rigidity, or equal use of metal.

"3. One has exposed and hence freely ventilated field-coils; the other has field-coils imbedded in the field-magnets.

"4. One has a large polar clearance, and consequently ample bearing-wear; the other has an armature clearance of about only one-third as much, and hence limited bearing-wear.

"5. One is operated with a high magnetic flux, and consequently high torque for given armature-conductor current; the other has a weak field, and consequent lower armature torque.

"6. One has a moderate sized armature and commutator, and runs at a moderate speed; the other, with equal capacity, has a much larger diameter of armature and commutator, and runs at a much higher speed.

"7. One permits of a low gear-reduction, and consequently a large gear-pitch; the other requires a higher gear-reduction, and a weaker gear-pitch.

"8. The windings of one are subject to electrical strains of one character; in those of the other the strains are of rapidly variable and alternating character.

"9. The mean torque of one is the corresponding maximum; the mean torque of the other is only about two-thirds of the maximum.

"10. The torque of one is of continuous character; that of the other is variable and pulsating, and changes from nothing to the maximum fifty times a second.

"11. One has two or four main poles only, two paths only in the armature, and two fixed sets of brushes; the other has four to fourteen poles, as many paths in the armature, leading to unbalancing, and as many movable sets of commutator brushes.

"12. One can maintain a high torque for a considerable time while standing still; the other is apt to burn out the coils, which are short circuited under the brushes.

"13. In one, all armature-coil connections are made directly to the commutator; in the other, on the larger sizes resistances are introduced between the coils and every bar of the commutator, some of which are always in circuit, and the remainder always present.

"14. In one the sustained capacity for a given weight is within the reasonable requirements of construction; in the other it is only about half as much.

"15. Finally, the gearless type, with armature and field varying relatively to each other, is available for one, but this construction is denied to the other.

"Consideration, then, of the characteristics peculiar to each class of motor indicates not that the single-phase motor cannot be used, but that if adopted the weight or number, and the cost of locomotives or motors required to do the work must be much greater; that the depreciation of that which is in motion will be much higher; and that there will always be an excess weight of fixed amount per unit which must be carried irrespective of the trailing or effective loads. We must, therefore, in many cases be led to the selection of the direct-current motor, that motor which has the higher weight capacity, the greater endurance, and the lower cost per unit of power."

In discussing this paper Storer criticizes each point in turn as quoted below.[1]

"1. 'The input of current in one is continuous; in the other, intermittent.' Quite true, but the draw-bar pull is quite as effective in one case as in the other.

"2. The direct-current motor has a solid frame like the single-phase motor. It has, further, two or more laminated poles bolted in, and if the interpole construction is used has as many more relatively small and delicate poles. The alternating-current motor as built by the company with which I am connected has, in all sizes up to a diameter of 38 in. field punchings made in a single piece and built up and keyed in the frame, making it as solid a construction as an armature on its spider. The claim for less rigidity in the single-phase motor is, therefore, not sustained.

[1]Discussion of above paper by N. W. Storer, A. I. E. E. Vol. XXVI.

"3. 'One has exposed and hence freely ventilated field-coils; the other has field-coils embedded in the field-magnets.' It is known to most motor designers that coils in contact with iron will dissipate heat much faster than when in the open air. This is especially true of coils in an enclosed motor. I have repeatedly noticed that motor field-coils which have been removed on account of roasting, have shown the insulation in contact with the pole pieces to be in good condition, while other sides were badly roasted. I know, therefore, that in respect to ventilation of field-coils, the single-phase motor is superior to the direct-current motor. Smaller cross-section of coils also allows the heat to be radiated better in single-phase motors, and the fact that a large part of the loss in the motor is concentrated in the field iron will enable the motor to dissipate a much larger amount of heat for a given temperature-rise than will a direct-current motor.

"4. Concerning 'polar clearances.' Many thousands of direct-current motors are to-day in operation with a clearance of 1/8 in. to 3/16 in. between poles and armatures, and in practically all cases where more than 3/16 in. clearance is used it is for electrical reasons. Further, while the smaller air-gap used for single-phase motors was at first much feared, the fears have proved to be without foundation and the present clearances of from 0.1 in. to 0.15 in. have proved to be ample and fully as good as 0.15 in. to 0.25 in. in direct-current motors, because there is no unbalanced magnetic pull.

"5. Concerning 'torque.' The torque of an armature is the pull it will exert at one-foot radius. Therefore it makes no difference in the result whether it is obtained with large flux and few armature conductors, or *vice versa.*

"6. 'A much larger diameter of armature and commutator, and runs at a much higher speed.' This is a very general statement: what are the facts? The armature diameters ordinarily run from 5 to 15 per cent. larger than for direct-current motors of corresponding output. It is undoubtedly true that the armature speeds of the earlier single-phase motors were much higher than the speeds of corresponding direct-current motors; at the present time, however, the speed at the nominal rating of the

motor is practically the same as that of direct-current motors, and the maximum operating armature speeds are within the safe limits set for direct-current motors.

"7. Concerning 'gear-reduction and gear-pitch.' The gear-reduction depends, of course, upon the speed; and as far as gear-pitch is concerned, I wish to say that the same gear-pitch is used for single-phase motors as for direct-current motors of the same capacity.

"8. 'The windings of one are subject to electrical strains of one character; in those of the other the strains are of rapidly variable and alternating character.' No conclusion is drawn from this. It may be of interest to know that there have been a number of instances where the single-phase motor has broken down in service on a direct-current section of the line, necessitating cutting it out of the circuit; but when the car reached the alternating-current section of the line it has been again connected in circuit and operated satisfactorily, thus indicating that the electrical strains with alternating current are less severe than with direct current.

"9 and 10. Concerning the 'variable torque of the single-phase motor.' No comment is made as to the relative merits of uniform or pulsating torque. In a recent discussion before the Institute, Mr. Potter called attention to certain characteristics of the torque exerted by an alternating-current motor, especially when it reaches the slipping point of the wheels. It was stated that there is an apparent advantage in the pulsating torque, because, when the motor starts to slip it does not immediately decrease its mean torque, as is done in the case of the direct-current motor, but slips in a series of jerks, apparently regaining the hold on the rail at every pulsation.

"11. Concerning the 'number of poles.' The paper states that the direct-current motor has 'two or four main poles only.' No direct-current motors built in the last 15 years except those on the New York Central locomotives have less than four poles. The paper states that the alternating-current motor has 'eight to fourteen poles.' The single-phase motors built by the company with which I am connected have four poles for all sizes up to and including 125 h. p. The largest single-

phase motor thus far built has a capacity of 500 h. p. It has but 12 poles.

"12. Concerning 'a high torque while standing still.' As we understand the matter, railway motors are designed to move a train rather than to hold it at rest. At the same time we know that the single-phase motor is amply protected against mistakes of motormen in leaving the current on the motor for a half-minute or so with brakes set.

"13. Concerning 'resistance in commutator leads.' It is well known that the resistance leads used in single-phase armatures are for the purpose of reducing to a minimum the loss due to the transformer action in the short-circuited coil. Their presence is fully justified and the efficiency is higher than it would be if they were not used.

"14. This refers to relative weights concerning which I shall have something to say farther on.

"15. On this point I agree absolutely with the author. There is one type of construction to which the single-phase motor is not adapted. This is so far employed in only a single case.

"More or less is said in the paper concerning the lower efficiency of the single-phase motor, and inference might be drawn that it is about 10 per cent. lower than that of the corresponding direct-current motor. Just to show what modern motors are capable of doing, I give below in parallel columns the efficiencies of corresponding sizes of direct- and alternating-current motors at different percentages of their full-load torque.

Per cent. of full-load torque	Direct current 90 h. p. motor	Alternating current 25-cycle, 100 h. p. motor	Direct current 200 h. p. motor	Alternating current 15-cycle, 200 h. p. motor
125	86.25	82.0	88.8	87.3
100	86.8	85.0	89.0	88.0
80	87.0	86.0	89.2	88.3
60	86.5	86.8	88.8	87.7
40	85.0	86.0	87.0	85.0
25	82.0	82.5	84.0	82.0

The added weight, lower efficiency, and lower acceleration for a given capacity of motor are not the only disadvantages of the alternating current system from the standpoint of rolling stock. As has been pointed out, it is nearly always desirable that cars equipped for alternating current service be able to enter cities upon direct current. While the alternating current single-phase series motor makes an excellent direct current motor, the control equipment for use upon either system is at best rather complicated and its first cost, weight and maintenance relatively high. The added complication of this combined control is at once obvious if a comparison be made of Figs. 104 and 110, while the tables listed below prove the rolling stock thus equipped to cost 28 per cent more, with a probable maintenance charge of 49 per cent. more than the 600 volt direct current equipment.

Referring to the 1200 volt direct current system, the motors are often of the 600 volt type which has been well standardized. Upon the city systems they operate as standard 600 volt equipment connected in parallel for full speed, while upon the 1200 volt trolley they are connected two in series for full speed operation. In cases where only half speed operation is required within the city limits, 1200 volt motors similar to the 600 volt type are used, the current capacity, of course, being less for a given car and extra insulation being provided for the higher voltage. Although the high voltage direct current equipment has not been standardized and thoroughly tried out in practice as yet, the dozen or more roads in operation are apparently giving satisfactory results, while the first cost and maintenance cost are but slightly greater than the low voltage system.

First Cost and Maintenance.—The relative merits of the three systems from the standpoint of first cost and maintenance expenses can best be illustrated by means of tables XXVIII and XXIX taken from a very able discussion of the subject before the American Institute of Electrical Engineers by W. J. Davis, Jr.[1]

[1] "High Voltage Direct Current and Alternating Current Systems for Interurban Railways," by W. J. Davis, Jr., A. I. E. E., Vol. XXVI.

TABLE XXVIII.

COMPARATIVE COST PER MILE SINGLE TRACK.

	D. C. 600 V.	D. C. 1200 V.	A. C. 6600 V.
Road bed, complete including grading, ballasting, etc.	$15,000	$15,000	$15,000
Trolley and feeder installed	3,800	3,000	2,100
Track bonding	600	530	488
Transmission line installed	1,500	1,500	1,300
Substation installed	2,200	1,600	600
Power station installed	2,450	2,450	2,570
Cars and equipment	1,800	1,970	2,300
Telephone	120	120	120
	27,470	26,170	24,470
Saving over 600 volts D. C.		1,300	3,000

TABLE XXIX.

RELATIVE OPERATING COST PER MILE SINGLE TRACK PER ANNUM.

(One hour headway).

	D. C. 600 V.	D. C. 1200 V.	A. C. 6600 V.
Car miles per day	64	64	64
Kw. hours per day at power house	275	275	245
Cost of coal per annum	$470	$470	$419
Cost of substation attendance	175	79	46
Maintenance of motors and control	94	117	140
Total	$739	666	605
Saving over 600 V. direct current exclusive of fixed charges.	....	76	134
Saving in fixed charges		137	315
Total annual saving	....	$213	449

The above comparative costs are based upon the following data:

Length of road, 50 miles or more.

Cars, 52 ft. over all, weighing 21 tons, without equipment or load and seating 56 passengers.

Car equipment, four 75 h. p. motors.

Maximum speed on tangent level track, 45 m. p. h.

Schedule speed, 24 m. p. h. including stops and slow running through towns.

Headway, maximum service, one-half hour.

Frequency of stops, one in two miles.

Average energy, 85 watt-hours per ton mile at car.

	D. C. 600 V.	D. C. 1200 V.	A. C. 6600 V.
Spacing of substations	10 mi.	22 mi.	32 mi.
Maximum trolley voltage drop	25%	25%	10%
Efficiency, generator bus bars to cars	71%	71%	84%
Average efficiency car equipment	75%	75%	73%
Average power factor of system	96%	96%	85%

Power Factor.—The last factor included in the above list emphasizes one other disadvantage of the single-phase system, *i.e.*, its low uncontrollable power factor. The direct current system has no apparatus on the car or between the car and the converters to lower the power factor and its converters may even permit the power factor of the transmission line to be raised. The single-phase system, with no converting apparatus offers no means of power factor control, while the power factor is lowered still further beyond the substation by car motors, transformer, steel messenger or trolley if used and rails. A lower power factor means higher proportional current for a given capacity with increased first cost of equipment and percentage losses.

Frequency.—Another much discussed factor is that of frequency, if the single-phase system is being considered. Although a frequency of 25 cycles has been standardized for power supply and lower frequency apparatus is at present special and therefore high in first cost and slow of delivery, the introduction and future standardization of a 15 cycle frequency for railway service has been seriously advocated by many railway engineers for the following reasons.

1. An increase of from 30 to 40 per cent. in output of a motor of given size.

2. Consequent reduction in motor capacity required.
3. Consequent reduction in first cost of motor equipment.
4. Higher motor efficiency.
5. Higher motor power factor.
6. Better commutation.
7. Less dead weight on axles.
8. Lower line losses.

In contrast to these advantages of low frequency may be listed the impossibility of supplying lighting loads from the same generators with this frequency, the already established standard of 25 cycles, unsatisfactory turbine design in small sizes and the higher cost and greater weight of transformers.

At present there is no 15 cycle railway system in this country and it rests with the engineers of the future to decide whether the above advantages of low frequency are to dominate the selection of equipment for the individual roads if alternating current traction be determined upon. The opinion has been often expressed by prominent engineers that if the single-phase railway motor can be improved, the elimination of the converting apparatus in the substation and the lower first cost of the entire system will soon bring about a more general adoption of single-phase traction. Whether the lowering of the frequency to 15 cycles is the means to this end or not is yet to be decided.

In conclusion, it may be said that the tendency in electric traction as in every other branch of electrical development is toward higher voltages. The advocates of direct current traction point out the advantages of the 1200 volt system over the once almost universal system operating at 600 volts. In a recent paper before the American Institute of Electrical Engineers a conservative estimate of the economy obtained by a 1200 volt direct current system as compared with the 600 volt system as far as the factors are concerned which are dependent upon choice of system was given as follows.[1]

First cost,	10 to 20 per cent.
Fixed charges,	10 to 18 per cent.
Operation and maintenance,	10 to 15 per cent.

[1] "The 1200 volt railroad: A Study of Its Value for Interurban Railways," by Charles E. Eveleth, A. I. E. E., Vol. XXIX.

If the argument be carried but a step farther, the favored system of the near future would naturally be that one capable of transmitting power to the car at still higher voltages, which seems to point at present to alternating current propulsion of cars. This tendency in the near future should be greatly strengthened by the possible elimination (with the alternating current system) of the converter substation and its attendant operating troubles and expense and the lower first cost of the latter system where taken as a whole. All history of science and engineering is opposed to the feeling that the present condition of the alternating current system is as efficient and simple as it can be made and it therefore seems quite probable that the few unsatisfactory features of the alternating current motor and control design will soon be overcome and the single-phase system enjoy a much extended application to long distance traction. It will remain for the consulting engineer, however, to decide in each individual case upon the merits of the three or more systems, and the above statements should not be interpreted, therefore, as a prediction that alternating current traction will be eventually installed in all interurban developments nor that it necessarily is, or ever will be, the solution of trunk line electrification.

CHAPTER II.

Electric Traction on Trunk Lines.

The late E. H. Harriman is quoted in the New York Times as having said:

"But perhaps it is chimerical to think now of rebuilding the railroads of the entire country, and of replacing the entire railroad equipment. If so, what is the best thing? Obviously, electricity. And I believe that the railroads will have to come to that, not only to get a larger unit of motor power and of distributing it over the train load, but on account of fuel. That brings up another phase of the existing conditions. We have to use up fuel to carry our fuel, and there are certain limitations here just as much as there are in car capacity or motive power, particularly when you consider the distribution of the coal producing regions with respect to the major avenues of traffic. The great saving resulting from the use of electricity is apparent, quite aside from the matter of increasing the tractive power and the train load.

"The only relief which can be obtained through economics of physical operation must come through the outlay of enormous amounts of money such as would be involved in a general electrification or change of gauge."

This statement coming from such an eminent steam railroad authority, together with the already completed electrification of the terminals of the three large steam railroads entering New York, the Hoosac Tunnel of the New York, New Haven and Hartford Railroad, the Cascade Tunnel of the Great Northern and many other sections of former steam railroads throughout the country must convince the most prejudiced opponent of electrification that the time has come for the serious study of the problem of trunk line electrification. Thus far the electrification of steam roads has been adopted to meet special requirements or to solve peculiar problems in traction, such as the necessity of in-

creased service in large terminals, the avoidance of smoke in tunnels and the decrease of headway upon single track mountain grades. It may be safely predicted, however, that these special problems will gradually increase, the electrified terminal divisions gradually encroach upon the trunk line and eventually all will be electrically operated.

Probably the two paramount questions in the minds of steam railroad directors in connection with this problem are:

1. Can the service be improved with electric traction?
2. What will it cost to change and to operate and maintain the new system when installed?

While it seems advisable to consider these questions, especially the second, more in detail subsequently, a few of the minor advantages of electric traction on trunk lines, most of which are involved in the first question of possible improved service, will be first considered. The outline of the following brief discussion is one presented in great detail in the very valuable paper by Messrs. Stillwell and Putnam before the American Institute of Electrical Engineers.[1]

The factors entering into passenger service which contribute to the earning power of the electrified road to a greater extent than the steam railroad are:

Frequency of service.
Speed.
Comfort of passengers.
Safety.
Reliability of service.
Increased capacity of line.
Frequency of stops.
Convenient establishment of feeder lines.

Frequency of Service.—Experience with high speed interurban lines paralleling steam lines, but offering much more frequent service as illustrated in Table III, Part I, leads to the conclusion that frequent service creates traffic and therefore increases earning power. The frequent service offered by an electrified system is usually impractical with steam operation.

[1] "On the Substitution of the Electric Motor for the Steam Locomotive," by Lewis B. Stillwell and Henry St. Clair Putman, A. I. E. E., Vol. XXVI.

Speed.—Higher average speeds are possible and practical in electric service for four principal reasons.

a. The absence of reciprocating parts reduces danger of the locomotive leaving the track.

b. The absence of reciprocating parts reduces the maintenance of the track and the liability of broken rails.

c. The more rapid acceleration permits higher average speed with the same number of stops, or more stops with the same schedule speed.

d. For heavy trains requiring two locomotives, high speeds can be maintained by means of the multiple-unit control system. This is unsafe with two steam locomotives, as both engines cannot be controlled by a single engineer.

Comfort of Passengers.—The general comfort of passengers is greatly enhanced by the following features of electric traction:

a. Elimination of smoke and cinders.

b. Improved ventilation of cars made possible because of the absence of smoke and cinders.

c. More efficient and satisfactory car lighting possible, although unfortunately not always provided.

d. Easily controlled car heating.

Safety.—Several very notable elements of danger which are present in steam traction are eliminated when electrification is complete.

a. The power may be shut off by the train dispatcher to avoid collision.

b. The results of the absence of reciprocating parts which permit higher speeds to be maintained as outlined under the caption "Speed" also reduce the probability of accident.

c. If a collision occurs, the power may be promptly cut off if it is not accomplished automatically, as is usually the case.

d. The absence of the intense fire of the locomotive reduces the probability of fire in the wreckage.

e. The elimination of hot water and steam in locomotive and heating system reduces the dangers often resulting from such sources.

f. The absence of smoke in tunnels prevents errors in reading signals from that ca

g. Less likelihood of fire from electric lighting than from the oil or gas lamps commonly used upon steam roads.

h. The presence of a source of electrical power along the roadway and the necessary employment of electrically trained maintenance crews should decrease the first cost and maintenance, and therefore increase the use of automatic block signals.

It must be remembered, however, that in contrast to these advantages, the electrical distribution system, especially the third rail, offers a danger not present in steam railroad operation. Whereas the third rail may be protected, thereby reducing the danger under normal operation to a minimum, such protection would avail little in the case of a wreck. Under these circumstances the automatic circuit breakers must be relied upon to disconnect the section from the source of supply before serious physiological effects are produced or fires started in the wreckage.

Reliability of Service.—Comparison of the train delays from all causes, both electrical and mechanical, before and after electrification upon the few roads which have been operating sufficiently long by electricity to guarantee dependable results points to the conclusion that the service is more reliable after electrification than before.

For example, upon the Manhattan division of the Interborough Rapid Transit system of New York after electrification, the delay during the most severe months of the year for the exposed third rail system was but 72 per cent. of that under steam operation, expressed in train minutes, although an increased car mileage of 37 per cent. was maintained with the electric service.

Upon the electrified section of the New York, New Haven and Hartford Railroad during the heaviest traffic day of the year occasioned by the annual foot-ball game at New Haven, 128 regular trains and 30 special trains were operated between New York and New Haven in 1908 with but two delays totaling 17 minutes, while in 1909, 155 trains were run with no delays whatever.

The electrified system of the Grand Trunk Railway in the St. Clair Tunnel has operated six single-phase locomotives, each

averaging about 100 miles a day for a year, with but one delay and that of eight minutes duration.

When it is remembered that the train detention due to motive power troubles expressed in a percentage ratio of the actual motive power trouble delay in minutes to total train minutes delay from all causes upon an electrified road is but 8.5 per cent. and that this small percentage has been materially reduced over that of steam service, it may safely be said that present operation of electric locomotives is very reliable.

Increased Capacity of Line.—One of the marked advantages of electric traction is its large tractive effort for a given size and weight of equipment. While this feature is pronounced in the electric locomotive because of the elimination of the tender and the possible use of such a design as to throw practically all the weight of the locomotive upon the drivers, the effect is still more marked if motor cars be used, thus making practically the entire weight of train available for tractive effort between wheels and track. With this relatively great tractive effort, much higher rates of acceleration are possible, which in turn permit smaller headway between trains and increased traffic capacity for a given track.

This is of particular value upon heavy grades of the single track roads of the West, where electrification permits so great an increase in traffic over an existing single track that it obviates the necessity of double tracking the road for some time to come. In this case the cost of electrification may be balanced directly against the cost of a second track, which in the mountains of the West becomes a formidable figure.

Further, the length of freight trains using the steam locomotive is limited by the strength of the draft gear. With the use of two or more electric locomotives at the head of a train, or if the limit of the draft gear is reached, possibly the introduction of several locomotives throughout the length of the train, all operated by means of the multiple unit control from the leading engine will probably make possible a greatly increased freight traffic over a given road, thus increasing the freight as well as the passenger capacity of the line.

Frequency of Stops.—The ability of the electrically operated

train to make more frequent stops and thus better accommodate the riding public without reducing the schedule from that of the steam road has already been explained.

In addition to the above advantage in some instances it is possible to interconnect the local railway system with the electrified road in such a way as to transport passengers more nearly to their destination without change.

Both of the above features tend to increase the traffic and resulting earnings of the road.

Convenient Establishment of Feeder Lines.—With the reduced cost of power possible with an electrified trunk line, short branches of present steam roads or existing suburban or interurban lines may be operated electrically much more economically than at present. The large and efficient organization of the trunk line system also adds materially to this possibility. These short branch roads then become valuable feeders to the through trunk line.

Still further economy and convenience to passengers in such branch line operation may often be brought about by adding branch line motor cars to the through train at junction points, operating the entire train thus made up by the multiple unit system.

Improvement of Service.—It is believed that the first question to be asked by the directors of a steam road to which reference was made early in the chapter has been satisfactorily answered by the above improvements in the service, which have been shown to be possible upon electrified roads.

The possibility of increased draw bar pull and more rapid acceleration should, however, have more detailed analysis, for it is largely with regard to these features that service may be improved and earnings increased and therefore it is to these features to which the present steam railroad officials look at a time when service can no longer be increased with present locomotives since the latter have practically reached their maximum size and efficiency.

DeMuralt has worked out the following table to illustrate the relative values of maximum tractive effort available with various types of locomotives operating on level track at 60 m. p. h. to

which the author has added the last column, which more readily compares the locomotives upon a standard basis of unit weight. The locomotives selected for this calculation were the New York, New Haven and Hartford single-phase and the New York Central direct current locomotives operating in 1907 and a three-phase locomotive operated by the Italian State Railways compared with the most powerful Atlantic and Pacific type steam locomotives constructed.

TABLE XXX.

COMPARISON OF ELECTRIC AND STEAM LOCOMOTIVES.

	Max. Tract. effort lbs.	Wt. of locomotive and tender tons	Max. possible Trail. wt. tons	Max. T. E. per ton wt. of locomotive
Single-phase.....	4250	85	165	50
Direct current...	6000	95	258	63.2
Atlantic.........	9250	161	382	57.5
Pacific..........	9750	175	398	56.6
Three-phase.....	9375	95	457	98.6

From the above table it will be seen that the single-phase locomotives built at that time had a 13 per cent. lower tractive effort and the direct current locomotive a 10 per cent. higher effort than the most powerful steam locomotive, while the three-phase locomotive was capable of exerting 71.5 per cent. greater pull than the latter based upon unit weight of locomotive.

As values of maximum tractive effort have since been more than doubled in the case of the single-phase type and the Pennsylvania locomotive with its motors above the drivers has been introduced with a tractive effort 30 per cent. greater than the direct current locomotive of the above table, it may be seen that the largest steam locomotives are now far excelled in this respect.

Again, comparing present motor car operation in heavy service with that of the steam locomotive it is found that an eight car electric train in the New York subway develops a draw bar pull more than double the maximum value possible with the largest locomotive on the Erie railroad.

A most inspiring and graphic demonstration of the ability of

the New York Central locomotive, particularly in rapid acceleration, was the often quoted test carried out in 1904 on the New York Central Railroad when electric locomotive No. 6000, drawing eight Pullman coaches with a total train weigh of 478.5 tons, after reaching the same speed as the New York Central fast express was allowed to attain its maximum speed and was found to gain a full train length in the distance of one mile.

Cost of Electrification and Operation.—Granted that the service can be improved and the capacity of a road increased with electric traction as pointed out above, an answer to the second question must be found, *i.e.*, "What will it cost to change and to operate and maintain the new system when installed?"

The first cost of the change will vary greatly with local conditions and in any case would probably be prohibitive if undertaken for a complete trunk line system at once. Experimentation, if necessary at all, should be carried out upon some of the less important branches and the electrical rolling stock secured a portion at a time. It has even been suggested that as the purchase of new steam locomotives to replace those worn out or considered obsolete is usually treated by steam roads as an operation charge and not a charge against capital, the electrical rolling stock, or a large portion of it, might be secured in like manner and no great capital investment made for this portion of the new system.

The American Institute of Electrical Engineers was particularly fortunate at its 1911 annual convention to have presented by the Pennsylvania Railroad through Mr. B. F. Wood, a very detailed statement of the first cost and operating expenses of the electrification of the West Jersey and Seashore Railroad. While the figures for a larger trunk line operating locomotives in place of motor car trains would vary somewhat from those applying to this road as illustrated in the discussion which follows, the costs of this particular electrification which are the first to be made public in complete detail are well worthy of careful study. Tables XXXI and XXXII give total and unit costs of electrification, while operating expenses are well analyzed in Tables XXXIII to XXXVI inclusive. The costs apply to a total of 150 miles of single track upon which 47 to 52 ton cars are operated

in trains with two 200 h. p. motors per car controlled with the multiple unit equipment. The power station is of 8000 k.w. capacity supplying power to eight substations ranging from 1000 to 2500 k.w. each. The distribution voltage on the third rail system is 675 volts direct current.

TABLE XXXI.[1]

COST OF ELECTRIFICATION.

Power stations:		
Building, stacks, coal and ash handling machinery	$354,000	
Equipment	640,900	
Total		$994,900
Transmission line		241,500
Substations:		
Buildings	72,000	
Equipment	419,560	
Total		491,560
Third rail		557,636
Overhead trolley		80,500
Track bonding		102,659
Cars		1,135,900
Car repair and inspection sheds		46,674
Right-of-way, additional		592,100
Reconstructing tracks		763,800
Constructing new tracks		2,071,000
Terminal facilities and changes at stations		252,400
Signals and interlocking plants		561,900
Changing telegraph and adding telephone facilities		105,100
Fencing right-of-way, cattle guards, etc		88,400
Miscellaneous items		44,200
Total		8,130,229

TABLE XXXII.[1]

UNIT COSTS OF ELECTRIFICATION.

Power station, cost per kw	$124.36
Transmission line, cost per mile	3,485.00
Substations, building and equipment cost per kw	28.90
Third rail, cost per mile	4,235.00
Overhead trolley, cost per mile	4,120.00
Track bonding, cost per mile	684.50
Cars, including electrical equipment each	12,214.00

[1] "Electrical Operation of the West Jersey and Seashore Railroad," by B. F Wood. A. I. E. E. Vol. XXX.

TABLE XXXIII.[1]

POWER STATION OPERATION AND MAINTENANCE COST.

		Items	Year Total	Year Cent per kw-hr.
Operation.	Labor.	Boiler room	14,742.36	0.052
		Turbine	10,010.81	0.035
		Electrical	1,661.02	0.006
		Supervision janitors and watchmen.	2,756.23	0.010
		Total operating labor	29,170.42	0.103
	Material.	Coal	102,715.31	0.363
		Water	500.00	0.002
		Lubricants	....	....
		Misc. material	2,238.44	0.007
		Misc. charges	1,700.49	0.006
		Total operating material	107,154.24	0.378
		Total operation	136,324.66	0.481
Maintenance.	Labor.	Building	326.29	0.001
		Boiler room	1,550.44	0.005
		Turbine	836.11	0.003
		Auxiliary apparatus	844.17	0.003
		Electrical	195.30	0.001
		Piping	691.94	0.002
		Miscellaneous	187.30	0.001
		Total maintenance labor	4,631.55	0.016
	Material.	Building	146.63	0.001
		Boiler room	2,493.23	0.009
		Turbine	1,597.52	0.006
		Auxiliary apparatus	2,066.13	0.007
		Electrical	3,046.44	0.011
		Piping	383.97	0.001
		Miscellaneous	599.06	0.002
		Total maintenance material	10,332.98	0.037
		Total maintenance	14,964.53	0.053
Summary.		Total labor	33,801.97	0.119
		Total material	117,487.22	0.415
		Total labor and material station proper	151,289.19	0.534
		Other items charged to station accounts	2,160.60	0.008
		Total	153,449.79	0.542
		Net output	28,312,500	....
		Lbs. coal per kw-hr	3.246	....
		Cost of coal per 2000 lbs	$2.235	....

[1] "Electrical Operation of the West Jersey and Seashore Railroad," by B. F. Wood. A. I. E. E. Vol. XXX.

TABLE XXXIV.[1]

COST OF TRAIN OPERATION PER CAR MILE.

Year 1909.

	Repairs electric equipment of cars	Repairs passenger cars	Other maintenance of equipment costs	Electric power at car shoes	Yard service shifting costs	Motormen	Trainmen	Train supplies and expenses	Total	Other expenses	Total expenses	Car miles, total	Average cars per train
Avg...	0.68	1.10	0.25	4.30	0.33	0.88	1.44	0.69	9.67	9.08	18.75	4,107,609	3.457
Year 1910.													
Avg...	0.66	1.01	0.27	3.33	0.43	0.91	1.52	0.67	8.80	9.39	18.19	4,552,532	3.518

TABLE XXXV.[1]

COST OF TRANSMISSION SYSTEM MAINTENANCE.

1910.

	High tension		Overhead trolley		Third rail		Running track bonding	
	Total	Per mile	Total	Per mile	Total	Per mile	Total	Per mile
Total and avg. per mi. per mo.	$3,444.57	$4.10	$4,895.16	$36.70	$10,864.13	$6.46	$2,445.72	$1.36

TABLE XXXVI.[1]

COST OF SUBSTATION OPERATION AND MAINTENANCE.

1910.

	Total for eight substations				
	Operation	Maintenance	Total	Cost per kw-hr.	Substation output kw-hr. 675 volts direct-current
Year.....	$20,852.31	$3,607.30	$24,459.61	$0.001082	21,972,300

[1] "Electrical Operation of the West Jersey and Seashore Railroad," by B. F Wood. A. I. E. E. Vol. XXX.

In order to obtain an idea of the magnitude of the cost of electrification of the trunk lines of the United States, attention should be given to the estimates which have been made by Stillwell and Putnam,[1] particularly with regard to the effect upon this cost of a reduction of frequency to 15 cycles. Their estimate is based upon a continuous output of 2,100,000 k.w. from all the power stations combined. The power station apparatus such as turbines, transformers, meters, etc., which would be effected by frequency is estimated at $30 per k.w. at 25 cycles, or $33 at 15 cycles. Substation transformers would be increased one-third in first cost, so that the cost of electrical equipment in power house and substations would be increased from $70,000,000 to $80,000,000, with the decrease in frequency. The assumption is made, although open to serious question, that one electric locomotive, costing $25,000, will do the work of two designed for steam operation. With this assumption the aggregate cost of electric locomotives will be $600,000,000 at 25 cycles. The cost of these locomotives would be reduced with the change in frequency by possibly $1,000 each. Storer places this figure at $5,000. With the former and more conservative estimate the saving with the lower frequency on locomotives, is $24,000,000, which is more than double the increase in cost of power station and substation equipment. This points toward a conservatively estimated saving of $14,000,000 if the lower frequency be chosen.

Going a step farther into these rather astounding estimates the power station equipment for this general electrification figured at the low value of $100 per k.w. would amount to $210,000,000, with possibly an added $63,000,000 for substations and $600,000,000 for locomotives, etc., reaching a grand total estimated at one and one-half billions of dollars for the entire undertaking.

Upon the other hand, if the figures quoted by Murray[2] based upon actual observations of maintenance and operation costs upon the electrified section of the New York, New Haven and

[1] "On Substitution of the Electric Motor for the Steam Locomotive," by Lewis B. Stillwell and Henry St. Clair Putnam, A. I. E. E. Vol. XXVI.

[2] Discussion by W. S. Murray upon paper, "On the Substitution of the Electric Motor for the Steam Locomotive." A. I. E. E. Vol. XXVI.

Hartford Railroad are given serious consideration, it will be found that the above tremendous outlay is not confined to improvements in service and increased capacity of road alone, but that it will return dividends in the form of lowered operating costs and maintenance charges as well. For example, Table XXXVII. indicates the saving in coal per annum measured at the power house of the electrified system as compared with that used in the fire box of the steam locomotive performing the same schedule.

TABLE XXXVII.

	Ton miles per annum	Tons coal steam traction	Tons coal electric traction	Cost coal steam traction	Cost coal electric traction	Saving of elec. over steam
Express........	592,240,000	57,447	29,870	$183,830	$89,620	$94,210
Express local...	348,000,000	58,300	28,600	186,560	85,800	100,760
Express freight.	2,223,000,000	187,844	139,010	563,530	417,030	146,500
					Total saving.	$341,470

This means that the saving in coal alone on a short section of but one trunk line will amount to $341,470 per annum due to electrical operation, while further study of gains in maintenance leads to the conclusion that the cost of repairs of the electrical equipment will be but one-third or one-fourth that of steam locomotives. These two savings alone when capitalized for all the trunk lines of the country will go a great way toward balancing the seemingly excessive first cost of electrification estimated above.

Standardization.—If the prediction made earlier in this discussion prove true, and the electrified terminal and tunnel divisions of trunk lines gradually expand, as they seem to be expanding already, and ultimately they desire to merge together and exchange equipment in order that through service may be maintained over several roads, if one system has selected the 600 volt direct current third rail supply as in the case of the New York Central, and another the high voltage alternating current trolley typical of the New York, New Haven and Hartford, but possibly of another frequency and still other mountain divisions expand the territory operated with three-phase power, it can readily be seen that a situation will result fully as serious as the attempted

combination not long ago of roads of different track gauges and of cars with and without standard air brake equipment. George Westinghouse did not sound the warning of standardization any too early, therefore, in his recent paper before the London convention previously alluded to, when he said:

"For the present it may be a matter of little moment whether different systems have their contact conductors in the same position, or whether the character of the current used is the same or different. As previously stated in the early days of railroading, it was of little consequence whether the tracks of the different systems in various parts of the country were alike or unlike, but later it did make a vital difference, and the variation resulted in financial burdens which even yet lie heavily on some railways. It is this large view into the future of electrical service which should be taken by those responsible for electric railway development."

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